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GEOTHERMAL RESOURCES ASSESSMENT IN HAWAII*

DONALD M. THOMAS

Hawaii Institute of Geophysics, University of Hawaii, 2525 Correa Road, Honolulu, Hawaii 96822, U.S.A.

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Abstract—The Hawaii Geothermal Resources Assessment Program was initiated in 1978. The preliminary phase of this effort identified 20 Potential Geothermal Resource Areas (PGRAs) using available geological, geochemical and geophysical data. The second phase of the Assessment Program undertook a series of field studies, utilizing a variety of geothermal exploration techniques, in an effort to confirm the presence of thermal anomalies in the identified PGRAs and, if confirmed, to more completely characterize them. A total of 15 PGRAs on four of the five major islands in the Hawaiian chain were subject to at least a preliminary field analysis. The remaining five were not considered to have sufficient resource potential to warrant study under the personnel and budget constraints of the program.

The results of these studies have allowed us to attempt an estimate of the probabilities of low- to moderate-temperature (50 – 125°C) and of moderate- to high-temperature (125 – 360°C) geothermal resources in 12 of the survey areas; inadequate data or interpretational difficulties did not allow a valid estimate to be made for the remaining three study sites. Table 11 presents estimated probabilities for these PGRAs that are based on all currently available data.

The results of these studies have also demonstrated that no single surface geothermal exploration technique is capable of providing unequivocal proof of a subsurface thermal anomaly under all field conditions; it is more frequently the case that an estimate of the geothermal potential of a given PGRA must rely on a synthesis of all geological, geophysical and geochemical data available. Experience in the Kilauea East Rift Zone, a Known Geothermal Resource Area, has also demonstrated that none of the currently available surface exploration techniques are capable of yielding definitive information regarding the production capabilities of a specific parcel of a geothermal reservoir; the only technique that has proven capable of providing this information has been the drilling and flow testing of deep exploratory wells.

The island of *Kauai* (Figs 1 and 2) was not studied during the current phase of investigation. Geothermal field studies were not considered to be warranted due to the absence of significant geochemical or geophysical indications of a geothermal resource. The great age of volcanism on this island would further suggest that, should a thermal resource be present, it would be of low temperature.

The geothermal field studies conducted on *Oahu* focused on the caldera complexes of the two volcanic systems which form the island: Waianae volcano and Koolau volcano. The results of these studies and the interpreted probability for a resource are presented below.

Lualualei Valley: (Figs 1 and 3). Geologic mapping located the focus of the late-stage eruptive activity near the back of Lualualei Valley and tentatively identified the Waianae caldera boundaries within the valley. Soil geochemistry studies defined anomalous zones of mercury concentrations and radon emanation that appeared to be coincident with the caldera boundary faults. Groundwater chemistry and temperature measurements identified a distinctly anomalous well near the back of the valley and several others with slightly anomalous conditions on the caldera boundary faults. Geophysical soundings indicated low subsurface resistivities within the valley that were interpreted to correspond to warm fresh to saline water-saturated basalt. On the basis of the available data, the probability for a low- to moderate-temperature resource (50 – 125°C) within 3 km of the surface is assessed at 10 – 20%. The probability for a higher temperature resource is less than 5%.

Mokapu Peninsula and Koolau Caldera: (Fig. 3). Geologic mapping identified three post-erosional volcanic vents on Mokapu Peninsula; the inferred ages were on the order of 300,000 years. Geochemical studies on Mokapu were unable to identify a self-consistent pattern of soil geochemical anomalies or significant groundwater chemical anomalies that would suggest a geothermal resource. Resistivity soundings determined subsurface resistivities that were consistent with cold seawater-saturated sediment. The probability for even a low-temperature geothermal source at depths of 3 km or less beneath Mokapu is considered to be less than 5%.

Results of preliminary soil geochemical studies and interpretation of available groundwater data to the south of Mokapu, within the Koolau caldera, suggest that some thermally induced alterations may be present. Interpretation of geophysical data indicates that the temperatures within the ancient Koolau

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magma chamber are less than 540°C and that the shallow subsurface resistivities show no evidence of thermal effects. On the basis of the rather sparse data currently available, the probability for a low- to moderate-temperature resource associated with the Koolau magma chamber is considered to be 10% or less.

Due to the anticipated small demand for geothermal power on the island of *Molokai* in the foreseeable future, only preliminary efforts were made to assess the potential for a resource on this island. An abandoned well reported to have produced warm water when it was first drilled during the 1930s was located, but temperature measurements were unable to detect anomalies within the open portion of the hole; collapse of the lower third of the bore did not permit access to the water table, however. Soil geochemical analysis did not indicate significant mercury concentrations or unusual alteration minerals in the vicinity of the well. In the absence of detectable anomalies from the preliminary investigation, further studies were not considered to be warranted. The probability for a resource on West Molokai is not considered to be high; however, sufficient data are not available to offer an estimated probability for a resource.

Geothermal assessment activities on *Maui* included an evaluation of the major rift zones and post-erosional volcanic vents on both West Maui volcano and Haleakala volcano. Field surveys conducted on West Maui yielded the following results (Fig. 19).

Olowalu and Ukumehame Canyons: extensive geologic mapping characterized the southwest and southeast rift zones of West Maui volcano and interpreted these structures to suggest a migration of the rift zone activity late in the formation of West Maui. Numerous late-stage alkalic and trachitic dikes and plugs were also identified in the survey area. Ground-water geochemical and temperature measurements identified distinctly anomalous water chemistry and temperatures. Resistivity sounding data for the area was interpreted to indicate a thick layer of warm, fresh to saline water beneath the Olowalu and Ukumehame Canyons. The probability of a thermal resource having a temperature greater than or equal to 50°C is estimated to be 50 – 60%, whereas a temperature greater than or equal to 125°C has an estimated probability of 10% or less.

Lahaina-Kaanapali: soil geochemical surveys were unable to identify a self-consistent pattern of soil mercury concentrations or radon emanation rates that would suggest a thermal resource. Groundwater temperature measurements and chemical analyses were similarly unable to detect significant thermal alterations. Geophysical soundings detected subsurface resistivities consistent with cold water-saturated alluvium and basalt. The probability of a thermal resource existing in this area is less than 5%.

Honokowai: groundwater chemistry and temperature data for this area were unable to confirm the existence of any thermal impacts and geophysical soundings indicated normal subsurface resistivities. Hence the probability for a resource in this location is believed to be less than 5%.

Field surveys on Haleakala were confined to the lower portions of the three major rift zones and yielded the following analyses:

Haleakala Northwest Rift: soil geochemical and groundwater chemical studies in this area both indicate potential anomalies. The interpretation of the anomalies with regard to thermal alterations was not, however, unequivocal. Geophysical soundings were unable to identify significantly anomalous subsurface resistivities or self-potential variations. The probability of a low- to moderate-temperature resource is placed at 10 – 20%, whereas that for a high-temperature resource is less than 5%.

Haleakala Southwest Rift: geologic mapping has determined that several flows on this rift are less than 10,000 years of age and that a few are less than 1000 years old. Preliminary geochemical studies were unable to identify unequivocal evidence of thermal effects on the lower rift zone area, whereas geophysical soundings indicated that thermal groundwaters may be present at depths of less than 3 km. The probability for a low- to moderate-temperature resource is estimated to be 30 – 40%, whereas that for a high-temperature resource is placed at 15 – 25%.

Haleakala East Rift Zone: preliminary geochemical and geophysical surveys were performed in this area. The results of these efforts did not identify significant anomalies; however, difficulties in interpretation and the small amount of data available do not allow an assessment of geothermal potential to be made.

The island of *Hawaii,* being the youngest and most volcanically active island in the Hawaiian chain, was found to have the largest number of PGRAs (Fig. 34). The current assessment program performed field surveys in six of the most promising PGRAs on Hawaii, which yielded the following results:

Kawaihae: geophysical surveys performed over this area indicate a set of magnetic and resistivity anomalies that suggest that an intrusive body, associated with the Puu Loa cinder cone, may be heating local groundwaters. Groundwater chemistry and temperature anomalies confirm the existence of a heat source in the vicinity; however, the temperatures are not indicated to be very high. The probability of a low- to moderate-temperature resource in the survey area is indicated to be 35 to 45% and a moderate- to high-temperature resource to be 15% or less.

Hualalai: geologic mapping on the western flank of Hualalai suggests that frequent eruptive activity has occurred during the last 5000 years. Geophysical surveys have identified distinct magnetic, resistivity and self-potential anomalies near the summit of Hualalai, whereas the lower western flank has not shown significant thermal effects. Geochemical data on the lower flanks were similarly unable to identify any obvious thermally induced anomalies. These data suggest that there is a 35 – 45% probability of a low- to moderate-temperature thermal resource near the summit of Hualalai and a 20 – 30% probability of a high-temperature resource in this area. Probabilities for comparable resources existing on the lower flanks are estimated at 15 – 25 and 5% or less, respectively.

Mauna Loa Southwest Rift: limited geophysical surveys performed on the lower southwest rift were unable to detect significant resistivity anomalies to depths equivalent to the local water table, and a self-potential traverse detected only one anomalous gradient that was interpreted to be the result of a downgoing streaming potential. No strong geothermal anomalies were identified; however, the limitations of the available data set do not allow a probability estimate to be made of the resource potential in this area.

Mauna Loa Northeast Rift: geophysical and geochemical field studies performed in this PGRA were unable to detect any evidence of a geothermal anomaly in this location. The probability for even a low-temperature resource is estimated to be less than 5%.

Kilauea Southwest Rift: geologic mapping has indicated several areas of steaming ground and warm coastal springs adjacent to the rift systems. A re-analysis of available geophysical data for this area concluded that warm groundwater was present within the rift zone. Magnetic anomalies observed over the rift indicate that subsurface temperatures may exceed the Curie temperature. The probability for a low- to moderate-temperature resource on this rift is considered to be 100%, whereas that for a high-temperature resource on the upper rift is estimated at 70 – 80%.

Kilauea East Rift Zone: an extensive body of geological, geophysical and geochemical data concerning the East Rift Zone is available and virtually all of this data indicates that a high-temperature thermal system is associated with the entire rift. Deep exploratory geothermal wells drilled into the rift zone have identified temperatures in excess of 350°C and continuous production from one of these wells for a period of more than two years indicates that sufficient recharge is available for production of geothermal electrical power. The probability for both a low- and high-temperature resource on this rift zone is 100%.

INTRODUCTION

The Hawaii Geothermal Resources Assessment Program was initiated in 1978 under the Western States Cooperative Direct Heat Resources Assessment Program. Its goal was to identify and evaluate Potential Geothermal Resource Areas (PGRAs) on all major islands of the Hawaiian chain. The first phase of the assessment effort entailed a review of publicly available data from which 20 areas within the state were identified (Fig. 1) where geological, geophysical or geochemical data suggested that a resource might be present (Thomas *et al.*, 1979).

One of the identified areas, the Kilauea East Rift Zone, was at that time considered to be a Known Geothermal Resource Area (KGRA) due to the discovery of a productive, high-temperature geothermal reservoir by the experimental well HGP-A (Kingston *et al.*, 1976; Chen *et al.*, 1979). The probability of the existence of a geothermal resource in the remaining 19 locations ranged from nearly 100% (e.g. areas of recent volcanism or known warm water resources) to less than 5% (areas identified on the basis of unconfirmed reports of warm water or decades-old water chemistry data).

The second phase of the Assessment Program consisted of a series of geological, geochemical and geophysical field surveys conducted in selected PGRAs in an effort to confirm the presence of a resource and to characterize a confirmed anomaly as completely as possible within the funding and personnel constraints of the program. The former constraint precluded any attempt to confirm or characterize a potential resource area by drilling and thus the current study was limited to surface exploration techniques. In order to operate most efficiently with the personnel and budget available for the program, those areas believed to possess the greatest potential as an economically viable energy resource were given the most intensive study. Areas in which either the resource potential or the interest in development was believed to be minimal were given a lower priority for field surveys.

The second phase of the Assessment Program, under Department of Energy sponsorship, has come to a close. The present report will review the results from the field survey program as well as data from studies conducted under the sponsorship of agencies other than DOE which are relevant to geothermal resources in Hawaii. Finally, an estimate of the potential for a geothermal resource in each of the identified PGRAs will be presented.

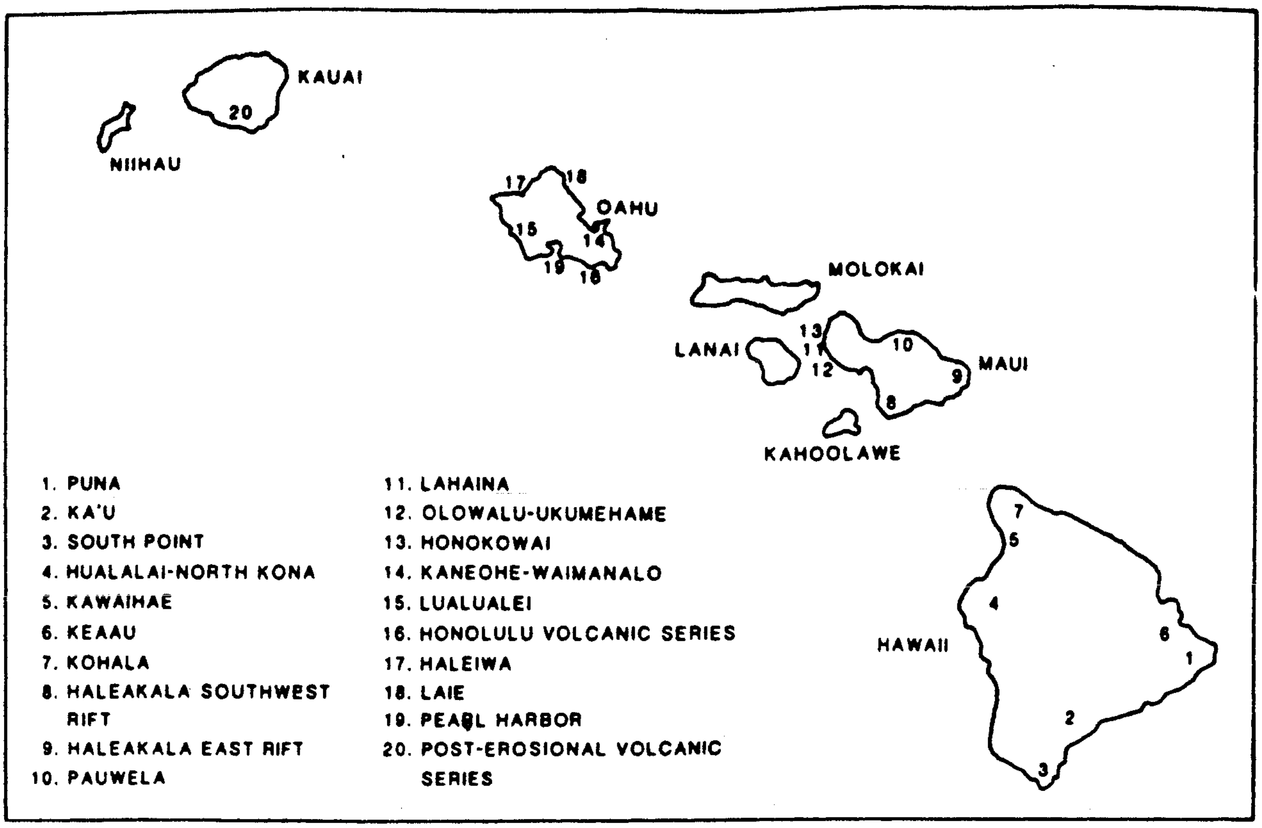


Fig. 1. Map of the major islands of the Hawaiian Archipelago showing the locations of Potential Geothermal Resource Areas identified during the preliminary phase of the Geothermal Resources Assessment Program. (From Thomas *et al.*, 1979.)

KAUAI

The island of Kauai is the northernmost and oldest major island of the Hawaiian chain (Fig. 2). It is made up of a single volcanic shield that completed its most active phase of volcanism nearly 3.3 My ago (Macdonald and Abbott, 1970). Intermittent post-erosional activity has occurred more recently, spanning a period from 1.4 to 0.8 My ago.

Groundwater geochemical data compiled for Kauai during the preliminary assessment identified a few very weak water chemistry anomalies, and although these anomalies could be interpreted to be the result of residual heat associated with Kauai's late-stage volcanism, the great age of this activity as well as the absence of any other detectable thermal effects suggests that this is very unlikely. Hence, further field studies on Kauai were not considered to have a high priority and therefore, no additional data have been acquired for this island.

The probability of a viable geothermal resource of even a moderate temperature (less than 100°C) existing on Kauai is believed to be 5% or less.

OAHU

Oahu is the second oldest major island in the Hawaiian chain and was formed from two independent volcanic systems (Fig. 3). The older of the two, Waianae volcano, was formed at least 2.4 – 3.6 My ago (Doell and Dalrymple, 1973), whereas the younger Koolau shield completed its most active phase of volcanism approximately 2 My ago (McDougall, 1964; Gramlich *et al.*, 1971). More recent post-erosional activity occurred only on Koolau volcano where approximately 40 separate vents, ranging in age from more than 400,000 years to less than 30,000 years (Macdonald and Abbott, 1970; Lanphere and Dalrymple, 1980), have been identified.

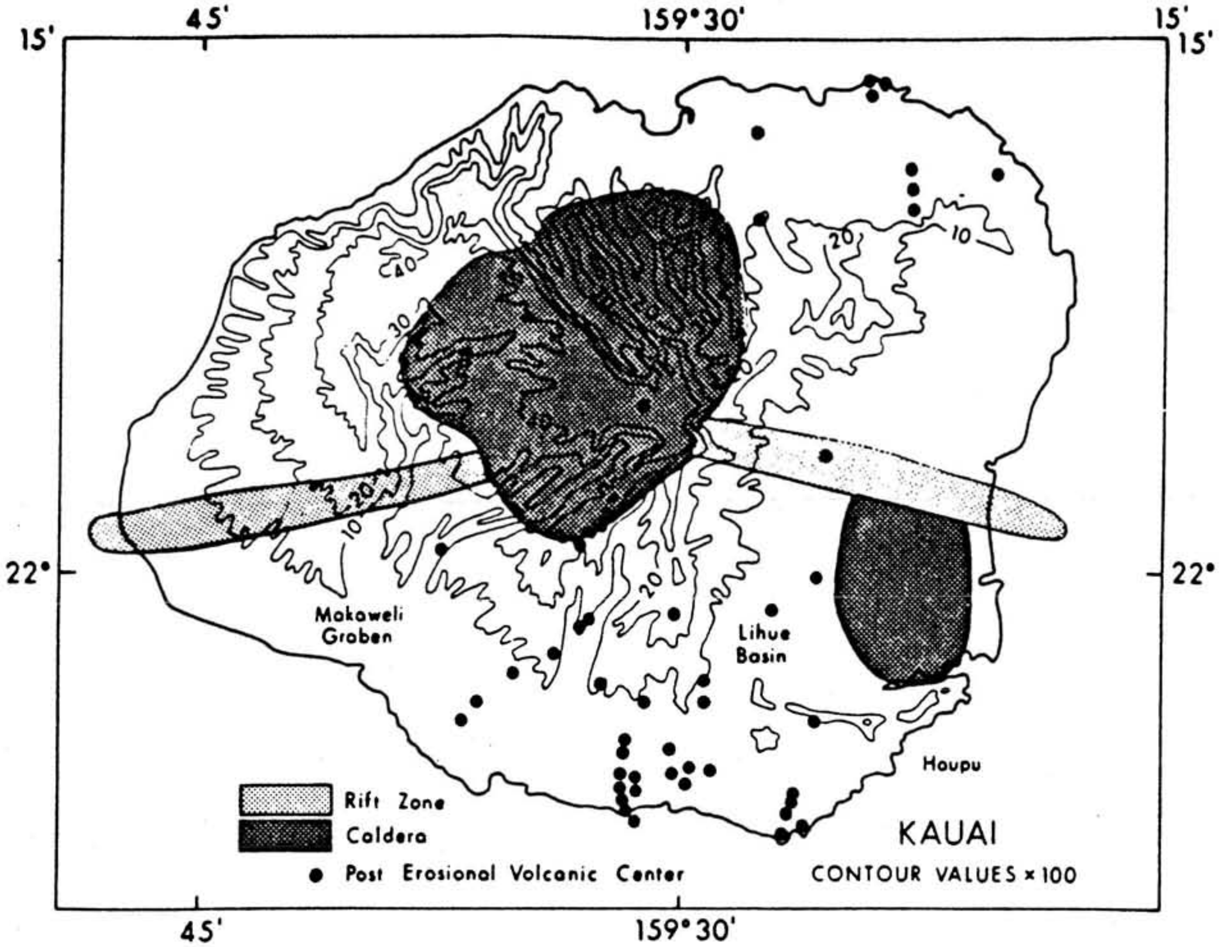


Fig. 2. Map of the island of Kauai. The inferred caldera and rift zones of Kauai volcano are noted as are the locations of the more recently active post-erosional vents. (From Thomas *et al.*, 1979.)

The preliminary assessment survey (Thomas *et al.*, 1979) identified six locations on Oahu where available geological, geochemical or geophysical data suggested that a thermal resource might be present (Fig. 3). Field surveys have been conducted in two of the more promising of these areas—Lualualei Valley and Mokapu Peninsula—during the current phase of the Resources Assessment Program.

Lualualei Valley

Lualualei Valley is located almost entirely within the inferred boundaries of the caldera complex of Waianae volcano. The valley is a superficial feature formed by subaerial erosion of the Waianae shield at a lower than present stand of the sea (Macdonald and Abbott, 1970). Deposits of silt and alluvium at higher sea levels formed the presently existing broad, flat valley floor.

Lualualei Valley was identified as a Potential Geothermal Resource Area primarily on the basis of reported groundwater geochemical and temperature anomalies together with limited geophysical indications of a geothermal resource. The geothermal evaluation studies conducted in Lualualei Valley under the current phase of research included geological mapping, groundwater chemistry and temperature measurements, soil mercury and radon mapping, and Schlumberger resistivity soundings (Cox *et al.*, 1979).

Geological mapping. Geological field studies in Lualualei Valley were oriented primarily toward identifying the lithology and structure of the Waianae caldera (Sinton, 1979). The

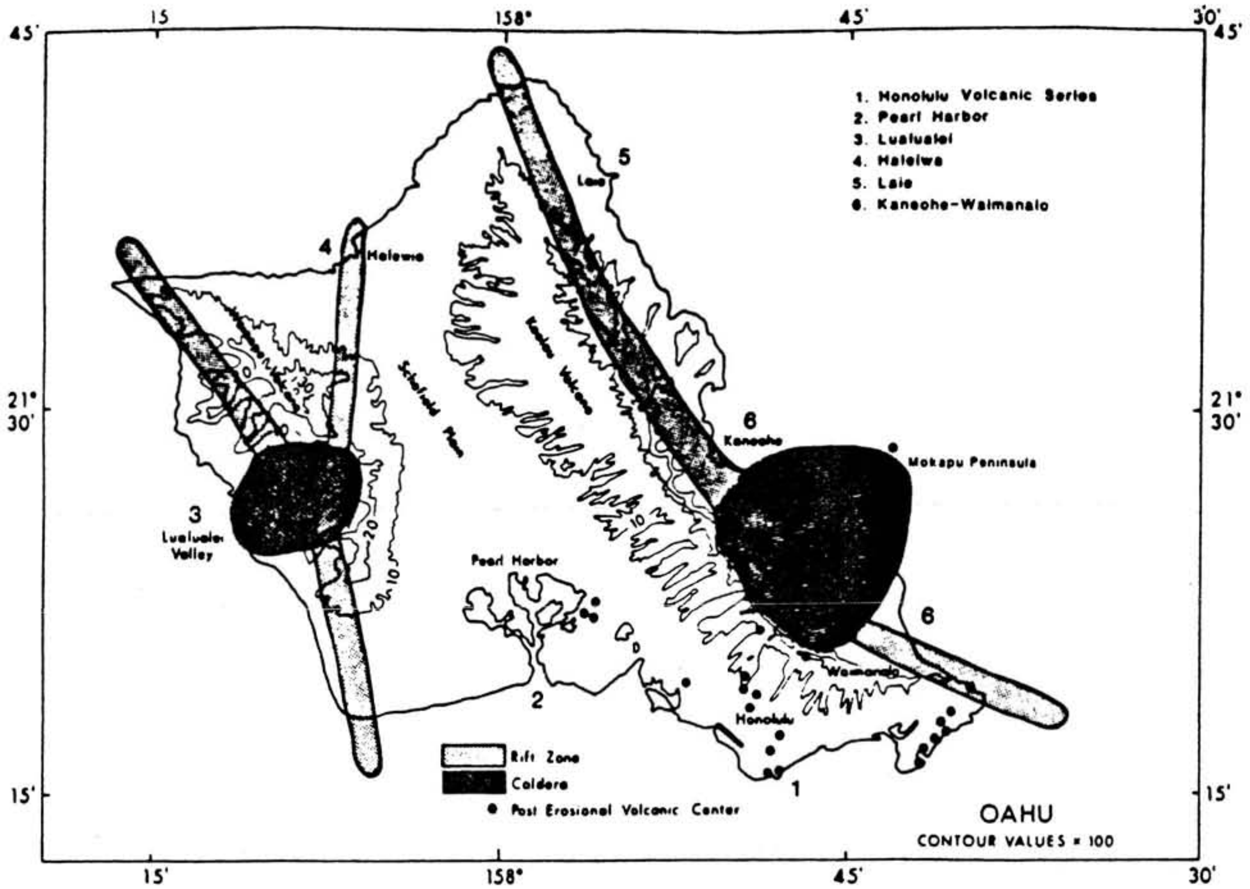


Fig. 3. Map of the island of Oahu showing the principal rift zones and calderas of Waianae and Koolau volcanoes. Potential Geothermal Resource Areas identified during the preliminary phase of the Geothermal Resources Assessment Program are also noted. (From Thomas *et al.*, 1979.)

lithologies present within the valley grade from older olivine-phyric basalts through plagioclase-phyric basalts to hawaiites (Fig. 4). Younger alluvial and marine sediments and conglomerates overlie the older volcanics and form the majority of the valley floor. The major lithologic units were found to be interlayered with erosional unconformities or soil horizons indicating that the volcano experienced significant periods of quiescence during its formation.

Analysis of the faulting within the valley has identified the approximate boundaries of the ancient Waianae caldera (Fig. 5) and suggests that deeply penetrating fractures accompanying caldera collapse may present permeable conduits through which surface groundwaters might circulate down to denser, possibly high-temperature rocks associated with the former magma chamber of Waianae volcano.

Geochemical surveys. Groundwater temperature and chemical surveys were performed in Lualualei Valley as a means of identifying surface aquifers that may have been affected by thermal fluids discharging from deeply penetrating, permeable fracture systems (Cox and Thomas, 1979). Water temperature measurements in wells and shafts in the valley were highly variable, spanning a range from 18 to 27°C (Table 1). The lower-temperature sources were generally associated with high-level, dike-impounded aquifers receiving extensive recharge from higher elevations. The higher temperatures were all measured on the valley floor in wells that penetrated basal aquifers. The temperatures observed in the basal aquifer, although higher than average for Hawaii, are not considered to be excessive in light of the relatively limited rates of low-elevation rainfall that provides recharge to this system. It may be significant, however, that the highest-temperature wells in the valley are located adjacent to the fracture systems believed to be associated with the caldera boundaries.

The extensive set of groundwater chemical data compiled for the wells in the valley (Table 1) showed that two of the primary indicators that have been commonly used in Hawaii for identifying geothermal potential (i.e. silica concentration and chloride to magnesium ion ratios) were anomalous in the groundwater of this survey area (Cox and Thomas, 1979). Several wells located on the caldera boundaries were found to have both moderate-to-high silica concentrations as well as above-normal chloride/magnesium ratios. Although neither of these indicators can be used as a quantitative indicator of subsurface temperatures, both strongly suggest that the groundwaters in this area have been altered by thermally driven rock/water reactions.

Another indicator of possible thermal influence, although not normally used extensively in Hawaii, is the sulfate to chloride ion ratios. With one exception, all of the wells in the valley appear to have normal SO_4/Cl ratios; the exceptional well is 2808-01 (Fig. 6) which, in the past, was noted to have one of the highest SO_4 concentrations of any well on Oahu (Mink, 1960). During its initial testing, this well was also noted to have had a sulfurous odor which, at the time, was inferred to be the result of sulfur-laden emissions from a geothermal system underlying the area (Mink, 1960).

Soil mercury and radon emanation surveys were performed over much of the accessible surface of Lualualei Valley (Cox and Thomas, 1979). The results of these surveys (Figs 7 and 8) delineated several areas in which soil mercury concentrations or radon emanation rates were substantially above normal background values. Some of these areas were apparently coincident with the mapped fracture systems associated with the caldera boundaries. However, some anomalous zones were identified well outside these areas. These results were generally interpreted to suggest the presence of at least low-level thermal effects associated with the caldera boundaries; however, it is apparent that other non-thermal influences are being detected as well.

Geophysical surveys. Three Schlumberger resistivity soundings were performed in Lualualei Valley (Mattice and Kauahikaua, 1979). The resistivity structure derived from these soundings indicated four distinct geoelectric units (Figs 9 and 10). Unit 1 was interpreted to be the surface alluvial valley fill. Unit 2 was identified as dry to partially saturated, weathered basalts. These surface layers were underlain by water-saturated layers. The upper layer, with a resistivity of 20 ohm·m to 28.2 ohm·m, was interpreted to be basalt saturated with fresh to brackish warm water; the basement layer had a resistivity ranging from 110 ohm·m to more than 240 ohm·m and was suggested to be the dense, intrusive complex associated with the former magma chamber of Waianae volcano. The depth of the interface between Unit 3 and Unit 4 was inferred to range from approximately 60 m below sea level at the back of the valley to more than 500 m at the mouth. Interpretation of the resistivity soundings suggests that the source of the warm water layer within the valley was the dense dike complex associated with the ancient magma chamber of Waianae volcano.

Geothermal assessment. Taken individually, each set of geophysical and geochemical data can be interpreted to be due to non-geothermal phenomena. However, the coincidence of atypical groundwater temperature and chemistry data, soil mercury and radon data, and subsurface resistivity data seems to indicate a common source for the anomalous conditions observed in this area. The most reasonable single source of the anomalies observed is believed to be a low-temperature thermal system associated with the caldera complex of Waianae volcano.

Fig. 4. Detailed geologic map of the Waianae caldera area (Oahu is.). Open circles denote the inferred boundaries of the Waianae caldera and solid lines signify access roadways. (From Cox *et al.*, 1979.) Legend on p. 443.

The present assessment of the geothermal potential for Lualualei Valley is that there is a 10 – 20% probability of a low- to moderate-temperature (50 – 125°C) resource existing at depths of less than 3 km; the great age of the caldera suggests that the probability of the existence of a moderate- to high-temperature (greater than 125°C) thermal resource within 3 km of the surface is less than 5%.

Mokapu Peninsula and Koolau Caldera

The Mokapu Peninsula is located on the windward (eastern) coast of Oahu at the northeastern edge of the Koolau caldera complex (Fig. 11). The peninsula is comprised primarily of calcareous, sedimentary material and small lava flows and tuff cones; the latter are

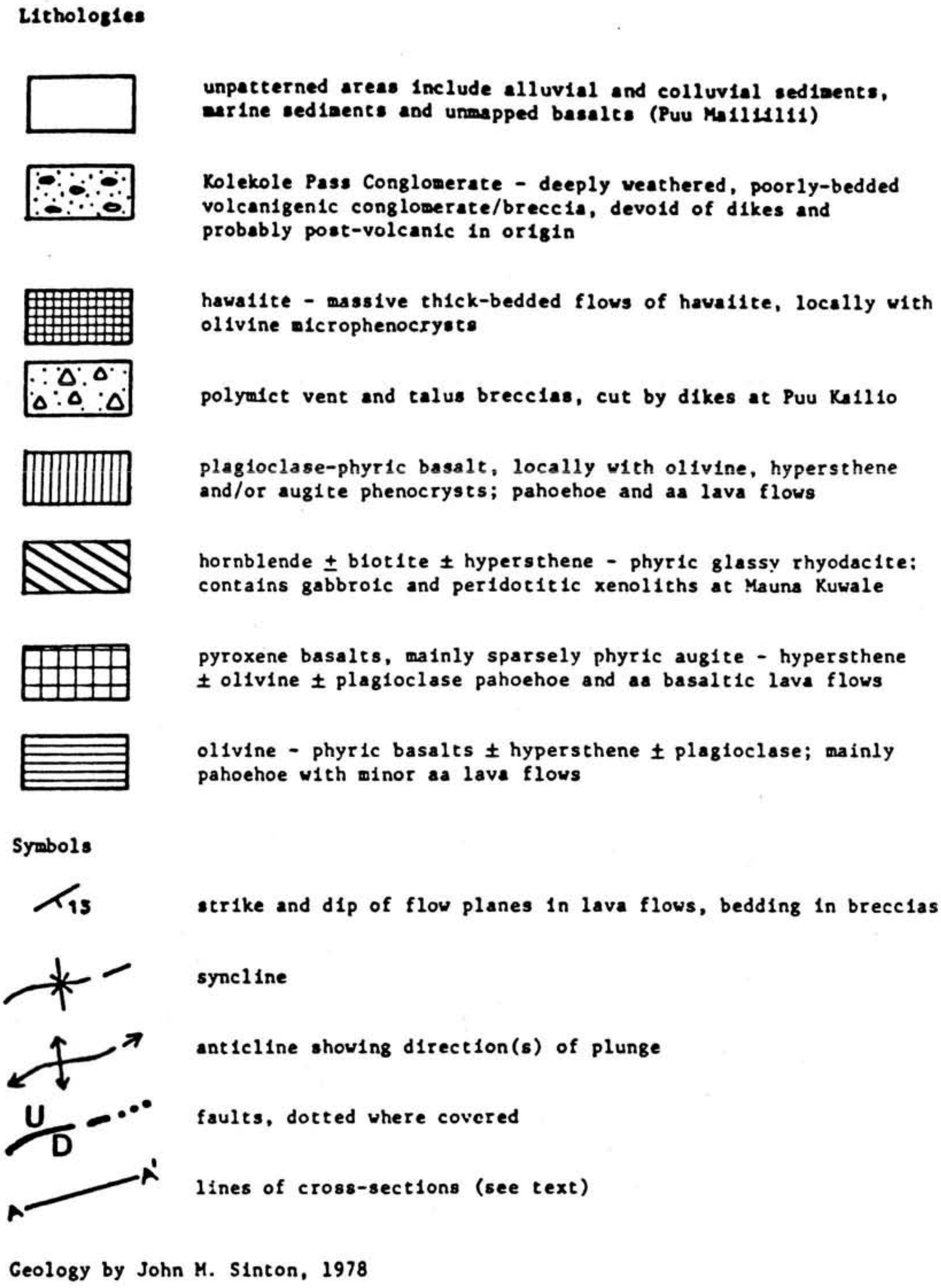


Fig. 4. Legend.

associated with the late-stage, post-erosional activity of Koolau volcano. The age of volcanism on Mokapu has been estimated to be at least 32,000 years before present and, more probably, is on the order of 400,000 years (Doell and Dalrymple, 1973).

The geothermal assessment program for Mokapu consisted of geological mapping, a limited set of soil mercury and radon emanation surveys, and three Schlumberger soundings (Cox *et al.*, 1982a). Due to Mokapu's proximity to the Koolau caldera, a limited number of geochemical surveys and geophysical surveys were also conducted within the caldera complex.

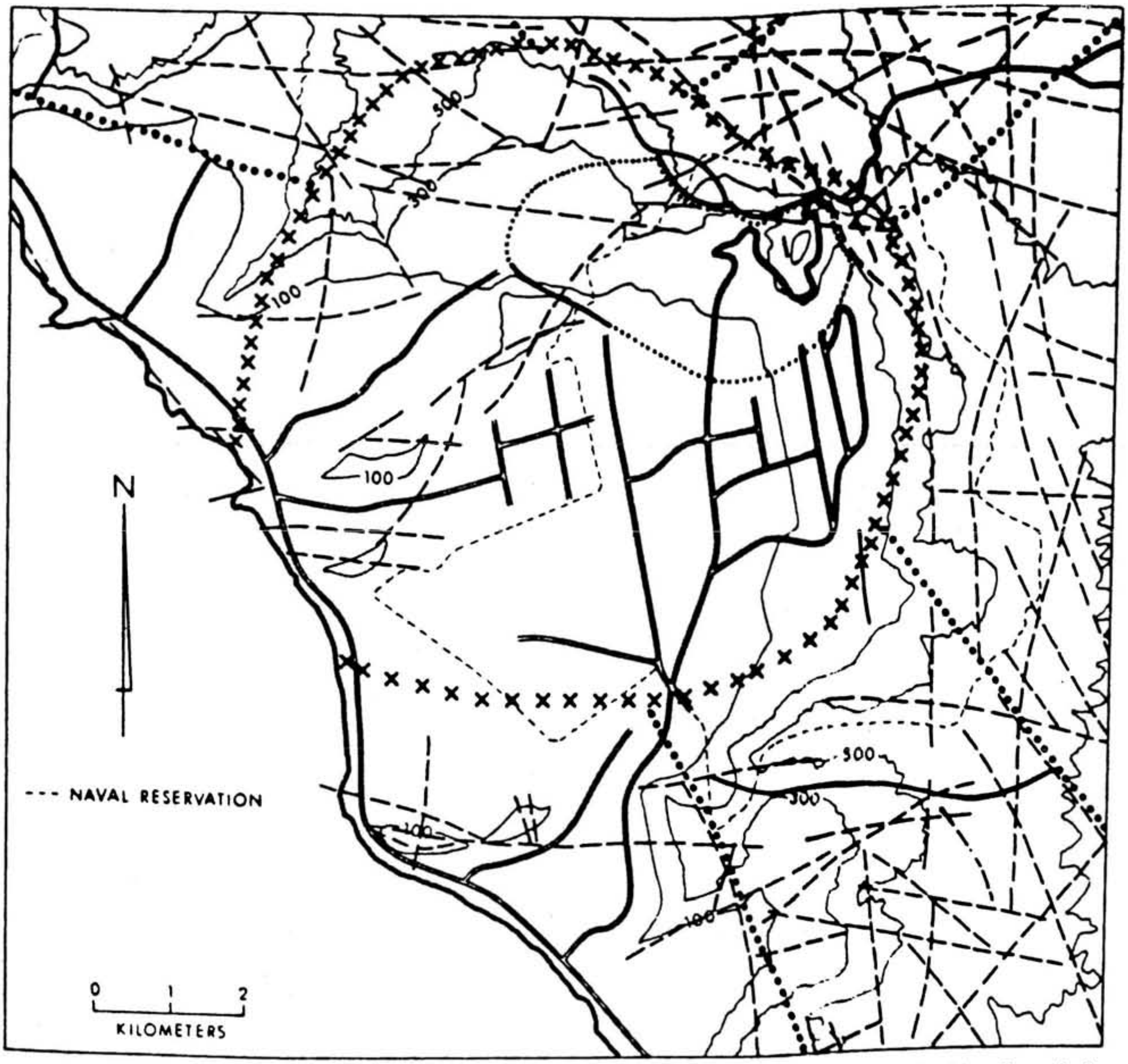


Fig. 5. Map of the Waianae caldera structural features (Oahu is.): crosses denote the inferred caldera boundaries; closed circles outline inferred rift zone trends; broken lines indicate air photo lineations; solid lines denote faults; dots outline the inferred focus of eruptive activity. The light double lines are access roadways. (From Cox *et al.*, 1979.)

Geological mapping. Geological mapping on Mokapu (Cox and Sinton, 1982) identified at least three separate volcanic vents within the study area and several other vents forming small islets around Mokapu. Pyramid Rock, located on the northern end of the peninsula (Fig. 12), appears to be the oldest of the three vents forming the peninsula. Puu Hawaiiloa, at the center of the study area, comprises the largest area on the peninsula and is believed to be at least 320,000 years of age. Ulupau Head is apparently the youngest vent on Mokapu and originally formed as a submarine vent that broke through the fringing reef around the peninsula.

Chemical analyses of the lavas from the post-erosional vents indicate that they bear no genetic relationship to the shield-building lavas of Koolau volcano and hence cannot be viewed as a renewal of Koolau's earlier activity (Cox and Sinton, 1982). The short duration of vent activity and the relatively small amount of lava emitted suggests that the probability of a remnant thermal resource being associated with Mokapu's post-erosional vents is very small.

Table 1. Water chemistry data for groundwater sources in Lualualei Valley, Oahu island

Source	Number	Locality	Temp. (°C)	pH	Na	K	Ca	Mg	Cl	F	HCO_3 + CO_3	SO_4	SiO_2	Total depth (m)	Date
HIG	2409-07	Maili	25.5		680	18.2	96	61	1410			232	172	22.3	9/78
HIG	2409-23	Maili	25.0		690	20.1	101	60	1480			178	157	22	9/78
HIG	2508-02	Lualualei	27.0		102	10.0	40	80	260			48	68	53.3	8/78
USGS	2508-02	Lualualei	29.0	7.8	92	7.9	36	102	292	0.2	338	22	92	53.3	10/71
USGS	2508-02	Lualualei	29.0	7.7	126	9.6	41	108	382	0.2	313	25	89	53.3	10/71
BH	2508-02	Lualualei		9.5	(136)		286	127	520		258	51	84	53.3	2/54
HIG	2508-07	Lualualei	25.5		380	12.8	127	81	1330			59	186	26.0	9/78
HIG	2607-01	Lualualei	24.0		41	2.9	14	12	41			58	96	137.5	8/78
USGS	2607-01	Lualualei	24.3	7.5	38	2.8	13	12	46	0.3	113	8.5	65	137.5	2/72
USGS	2607-01	Lualualei		7.1	39	2.9	9.6	8	50	0.3	117	10	80	120.4	6/67
USN	2607-01	Lualualei		6.7	28	3.0	7.2	8.5	48	0.3	105	8	78	120.4	1966
HIG	2609-X	Lualualei	24.0		90		95	50	141			7.8	41	6.4	9/78
HIG	2709-08	Lualualei	26.0		92	2.6	11	9.6	147			22	165	57.9	9/78
HIG	2712-01	Waianae	24.5		75	3.6	24	39	143			58	94	54.9	8/78
USGS	2712-01	Waianae		6.9	48	4.3	17	30	82	0.2	176	14	80	54.9	2/76
BWS	2712-01	Waianae		7.1	55	4.1	19	34	97	0.2	183	16	75	54.9	2/[illegible]
BWS	2712-01	Waianae			50	3.7	17	30	83	0.2	171	14	74	54.9	1/76
HIG	2808-01	Lualualei	26.5		120	4.0	116	27	138	0.6		260	81	163	8/78
USGS	2808-01	Lualualei	26.7	7.8	120	3.2	66	28	160	0.3	97	222	63	163	2/72
USN	2808-01	Lualualei	26.6	7.5					165		180	700		163	9/57
USN	2808-01	Lualualei		7.5					164		200	390	34	163	12/56
HIG	2808-02	Lualualei	19.0		19	3.0	11	6.5	23	0.12		33	58		8/78
USGS	2808-02	Lualualei	18.5	7.7	19	3.1	11	7.4	26	0.1	75	3.6	49		2/72
USGS	2808-02	Lualualei		7.2	19	2.8	11	7.3	26	0.1	74	4.6	49		2/72
USGS	2808-02	Lualualei		7.6	19	2.9	6.4	6	32	0.1	76	7.0	56		6/67
USN	2808-02	Lualualei		7.5	19	3.8	8.8	8.2	30	0.1	71	5.8	62		1966
USGS	2809-05	Waianae	21.5	7.4	63	0.2	36	3.7	68	0.05		0.1	62		1969
HIG	2809-06	Waianae	22.0		27	2.7	21	29	26			34	73		8/78
BWS	2809-06	Waianae	22.7	7.4	29	3.7	31	16	33		166	26	57		9/77
USGS	2809-06	Waianae		7.8	25	3.3	24	15	28	0.1	143	23	50		2/72
HIG	2809-06	Waianae	20.0		16	3.3	12	10	15			28	51		8/78
BWS	2809-06	Waianae	20.6	7.9	18	3.7	12	5.4	10		76	7.5	42		9/77
BWS	2809-06	Waianae	21.1	8.1	18	3.9	12	5.0	18	0.2	72	7.8	36		2/62
BH	2809-06	Waianae		7.6	(33.5)		16	8.7	22		75	14.5	40		8/58

Source = BH: Board of Health; BWS: Honolulu Board of Water Supply; HIG: Hawaii Institute of Geophysics; USGS: U.S. Geological Survey; USN: U.S. Navy.
Analyses in parts per million (ppm).
( ) = Na + K.

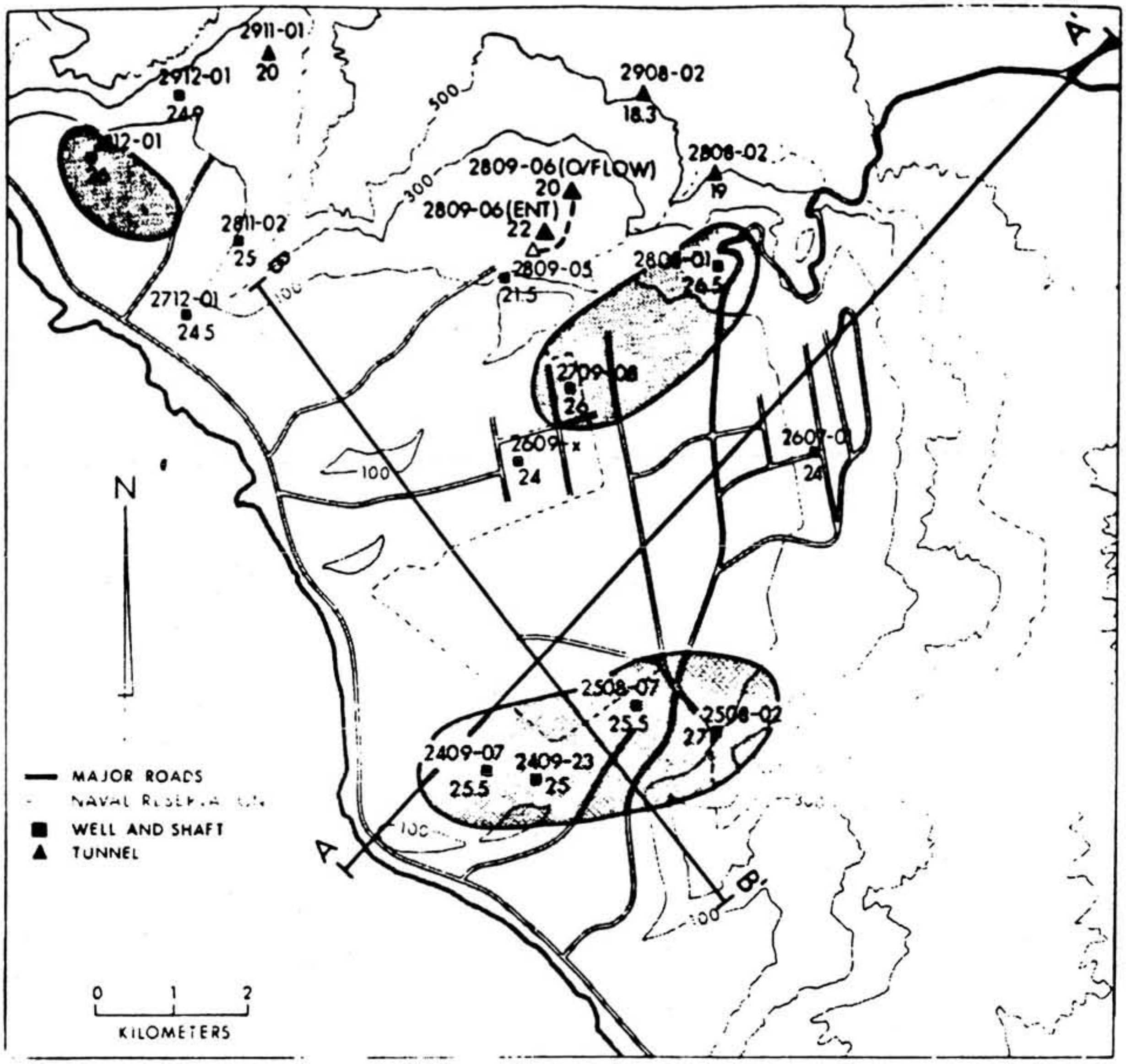


Fig. 6. Map of groundwater well, shaft and tunnel locations in Lualualei Valley (Oahu is.). The numbers presented adjacent to the groundwater sources are defined as follows: the lower number is the mean of published temperature measurements made at each well; the upper number refers to the U.S.G.S. identification code number. Three zones of apparently anomalous water temperatures are outlined. (From Cox *et al.*, 1979.)

Geochemical surveys. The high degree of cultural activity (e.g. residential areas, streets, jet runways, etc.) on Mokapu both limited the extent of the soil geochemical surveys performed and rendered their interpretation much more difficult. Soil mercury concentrations and radon emanometry data on the peninsula showed a few localized high values (Figs 13, 14), but no consistent correlation between the anomalous zones and geologic features could be identified (Cox *et al.*, 1982b).

Extension of the mercury survey to the Koolau caldera complex (Fig. 15) detected a broad range of soil mercury concentrations that were thought to be associated primarily with variations in soil type and rainfall rates. Although some association between the higher mercury zones and possible thermal effects was suggested, the temperature of the resource in this area was inferred to be relatively low due to the small magnitude of the observed anomalies.

Chemical analysis of groundwater from Mokapu was severely restricted by the absence of drilled wells; the only groundwater sources present were five shallow, brackish ponds. Chemical

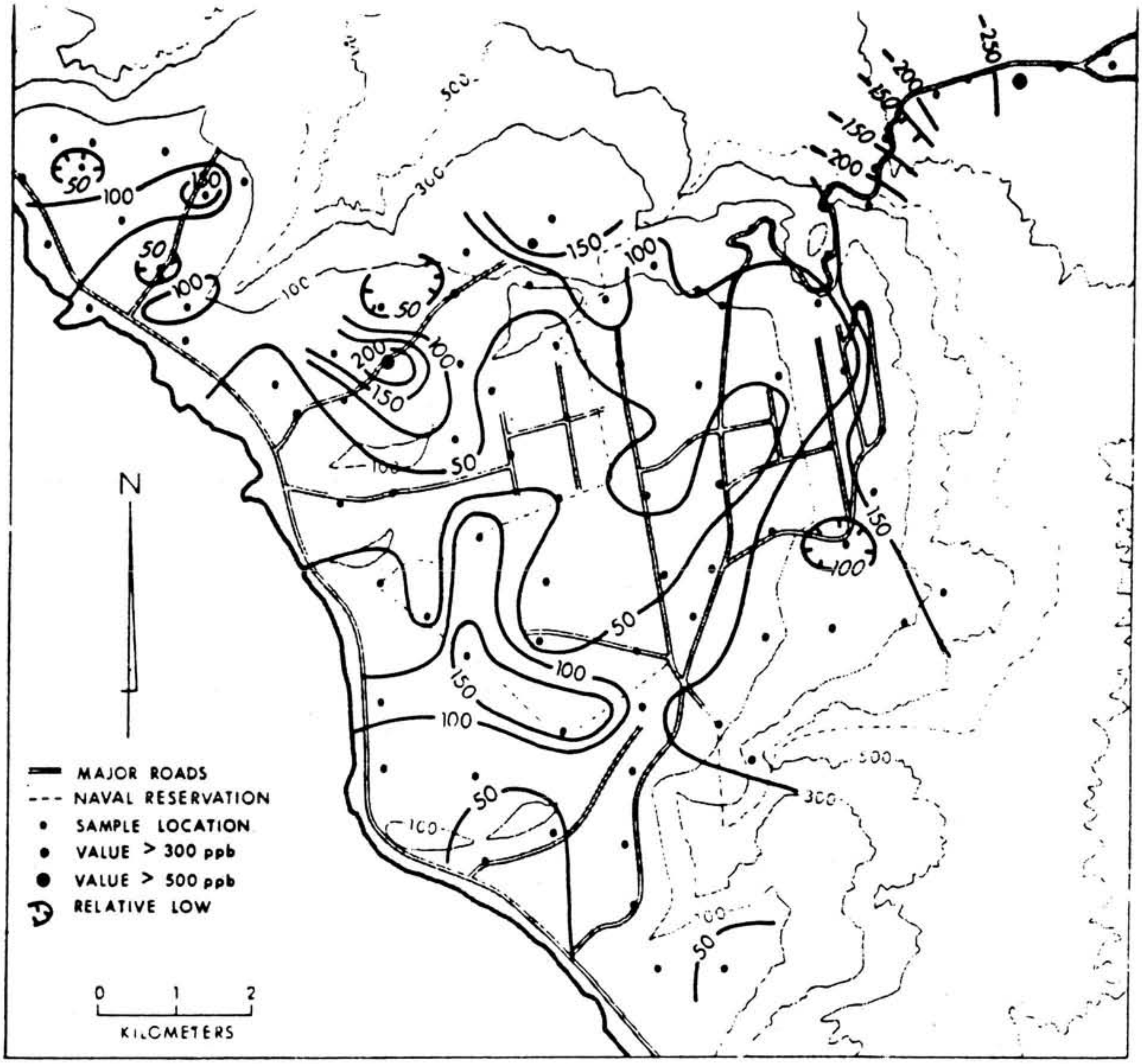


Fig. 7. Map of soil mercury concentrations found in Lualualei Valley (Oahu is.). Contour intervals are 50 parts per billion (ppb). (From Cox *et al.*, 1979.)

data indicated that all of the ponds consisted of seawater diluted by varying amounts of fresh surface water; no thermal alteration was revealed by the water chemistry (Table 2).

Available temperature and water chemistry data on the Koolau caldera area were also assessed as part of the Mokapu study. The results of this analysis (Table 2; Fig. 16) indicated that the majority of the ground-water sources in this area were typical of those found in the Hawaiian environment. However, two wells did have reports of anomalous conditions: one well had a reported (although unconfirmed) temperature of 30°C while the other had a chloride/magnesium ion ratio in excess of 15 ppm. Both of these wells are located on or adjacent to the Koolau caldera boundary faults and hence they may reflect thermal alterations.

Geophysical surveys. Geophysical surveys on Mokapu were restricted to three Schlumberger soundings (Fig. 17). The results of these soundings appeared to indicate a highly resistive surface section underlain by one or more layers of intermediate to low resistivity (Fig. 18). Basement resistivities in all cases were less than 3 ohm·m and were interpreted to correspond to alluvial layers saturated with cold seawater (Lienert, 1982).

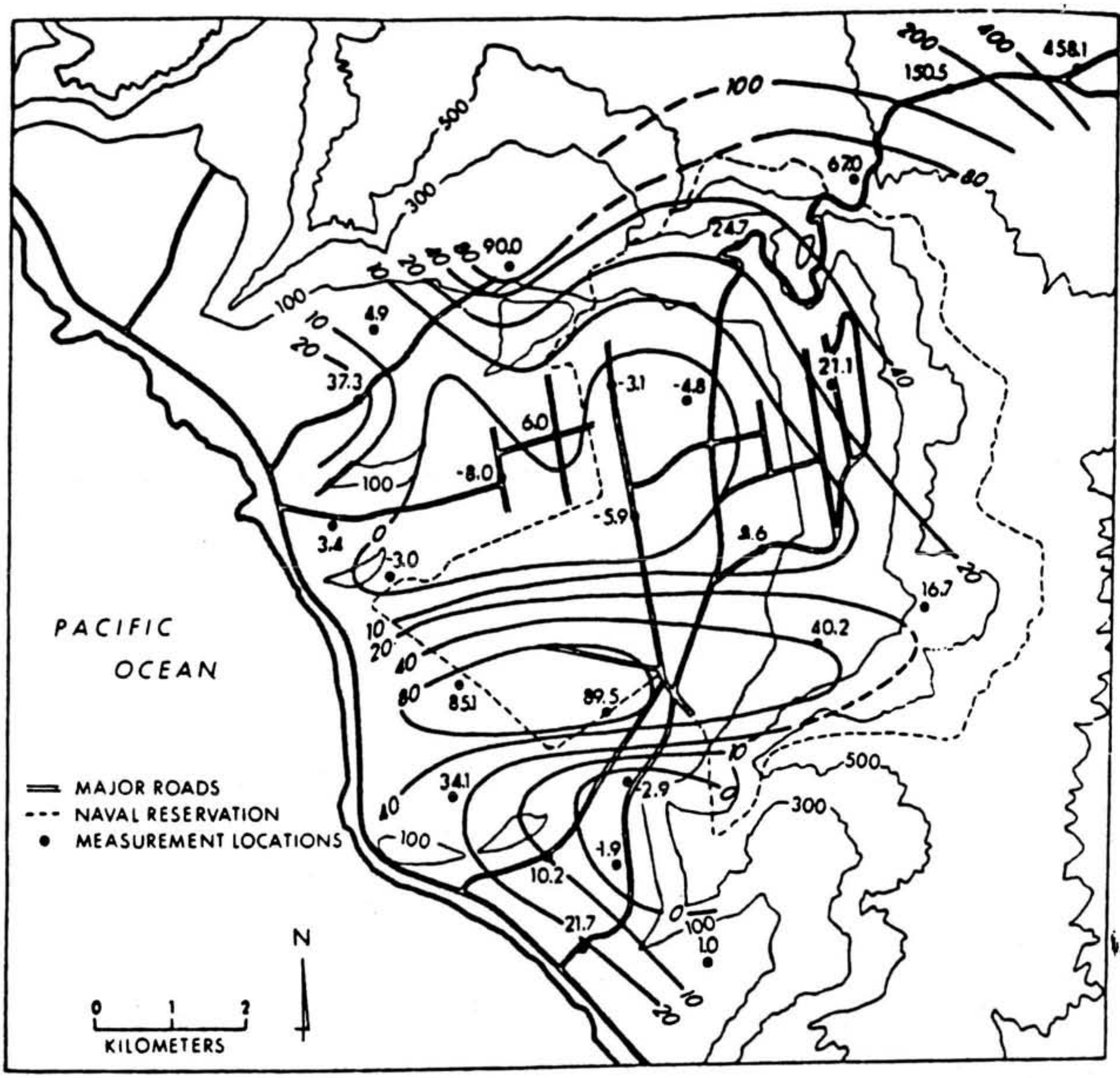


Fig. 8. Map of soil radon emanation contours in Lualualei Valley, Oahu island. Units are tracks per square centimeter per hour of exposure (× 100), corrected for soil background and contoured geometrically. (From Cox *et al.*, 1979.)

A separate geophysical analysis performed on the Koolau caldera area (Kauahikaua, 1981a) synthesized existing self-potential, gravity, seismic and aeromagnetic data with recently acquired resistivity soundings. An analysis of the observed remnant magnetization within the caldera complex suggested that subsurface temperatures ranged from less than 300°C to no more than 540°C. The resistivity data indicated that the electrical basement, to a depth of 900 m, had resistivities ranging from 42 ohm·m to more than 1000 ohm·m, which is considered to be within the expected range for basalts (or alteration suites) saturated by cold, fresh to saline water. No substantial effects on the resistivities were observed that were interpreted to be due to thermal influences. In the light of the geophysical data just reviewed, it may be assumed that if a thermal resource is associated with the Koolau caldera, its temperature is probably very low.

Geothermal assessment of Mokapu Peninsula and Koolau Caldera

The results of the geophysical and geochemical investigations on Mokapu Peninsula do not substantiate the existence of a potential geothermal resource in this area. Data acquired for Koolau caldera, although slightly more positive, indicate that if a geothermal system is

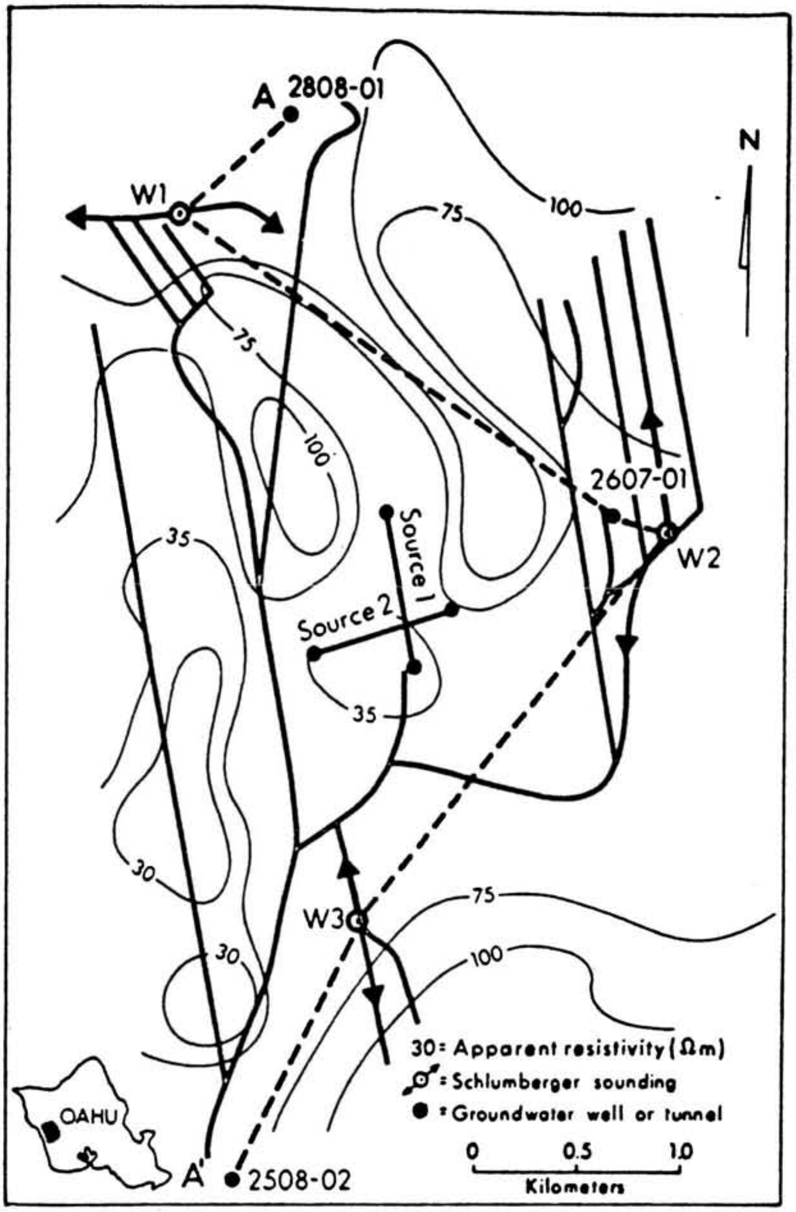


Fig. 9. Map showing the locations of Schlumberger sounding transects performed in Lualualei Valley (Oahu is.). (From Cox *et al.*, 1979.)

associated with residual heat in the ancient magma chamber, it is probably of a very low temperature. In assessing the geothermal potential of Mokapu Peninsula, the probability of a low- to moderate-temperature system (50 – 125°C) existing at depths of less than 3 km is estimated to be less than 5%; the possibility of a moderate- to high-temperature resource existing at similar depths is virtually nil. Assessment of the thermal potential of the Koolau caldera places the probability of a low- to moderate-temperature resource existing within 3 km of ground level at 10% or less; the probability of a high-temperature system existing at these depths is estimated to be less than 5%.

Assessment of geothermal potential of other PGRAs on Oahu

In the light of the results of the geophysical and geochemical studies conducted in the two areas on Oahu that, on geological grounds, would be anticipated to have the highest potential as geothermal resources, it is considered very unlikely that a viable geothermal resource will be found at depths of less than 3 km in the remaining four PGRAs that were identified during the preliminary geothermal assessment study.

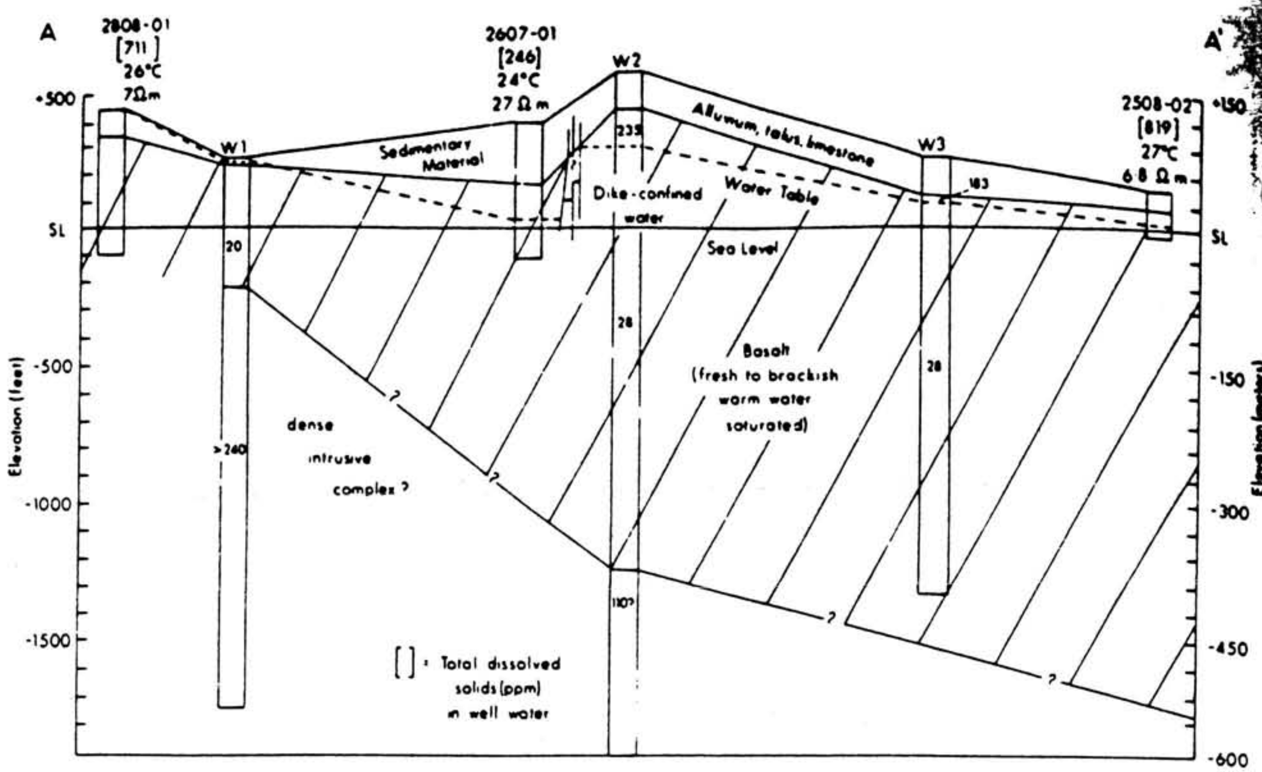


Fig. 10. Geoelectric cross section over Schlumberger traverse AA′ parallel to the caldera rim, Lualualei Valley, Oahu island (see Fig. 9). (From Cox *et al.*, 1979.)

MOLOKAI

The island of Molokai is the smallest of the major islands in the Hawaiian chain and was formed principally from two volcanic systems: East and West Molokai volcanoes. East Molokai was active during a period from 2.25 My ago to approximately 1.6 My ago: West Molokai was active from 1.75 My ago to 1.2 My ago (Macdonald and Abbott, 1970). A substantial period of post-erosional activity formed Kalaupapa Peninsula, the small shield on the north coast of Molokai, as well as a much smaller cone—now a separate island—at the eastern tip of Molokai.

The preliminary assessment survey identified one area on Molokai where a shallow groundwater well was reported to have encountered warm saline water.

Assessment surveys. Due to the very small potential market on the island of Molokai for geothermal energy, only a limited effort was made to confirm a resource in the identified PGRA. An attempt was made to locate the (now abandoned) water well that was reported to have encountered warm saline fluids. The well was located but had caved in above the water table and thus no water sampling was possible. Temperature measurements in the open portion of the well were performed, but no temperatures significantly above ambient were encountered. Several soil samples were also taken from around the well for mercury and mineral analysis; the mercury levels analyzed were well within the normal range for Hawaiian soils and the alteration suite present corresponded to normal weathering processes.

Due to the absence of any significant positive indicators for a resource and the low probability for utilization of a confirmed resource, no further field surveys on Molokai were attempted.

Geothermal assessment. The absence of any detectable geothermally related anomalies suggests that the probability of a viable thermal resource existing on Molokai is not very high.

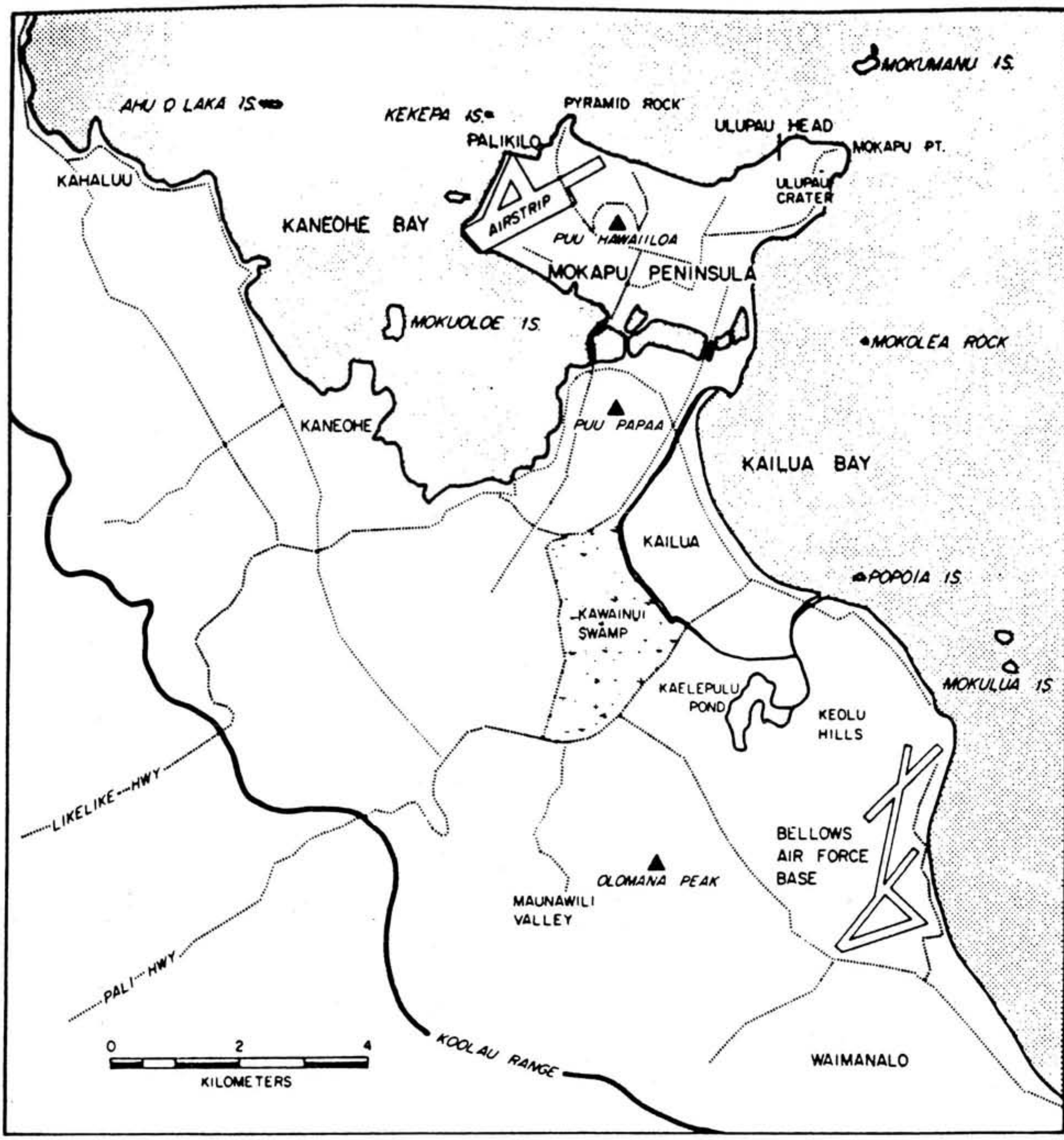


Fig. 11. Map of Mokapu Peninsula and adjacent area (Oahu is.). Roads are indicated by broken lines and the crest of the Koolau Range by an unbroken line. Solid triangles denote topographic reference points. (From Cox *et al.*, 1982a.)

However, the surveys that were conducted on this island were far from complete; hence an assessment of the geothermal potential on Molokai cannot be reasonably made on the basis of the data which are currently available.

MAUI

Maui is the second largest and second youngest island in the Hawaiian chain. It is made up of two independent volcanic systems: West Maui volcano, the older and smaller of the two, and Haleakala volcano.

Data compiled during the preliminary assessment surveys indicated that six locations on Maui (Fig. 19), three on West Maui and three on Haleakala, might have potential as geothermal resources (Thomas *et al.*, 1979). Field surveys were performed in all six PGRAs in an effort to

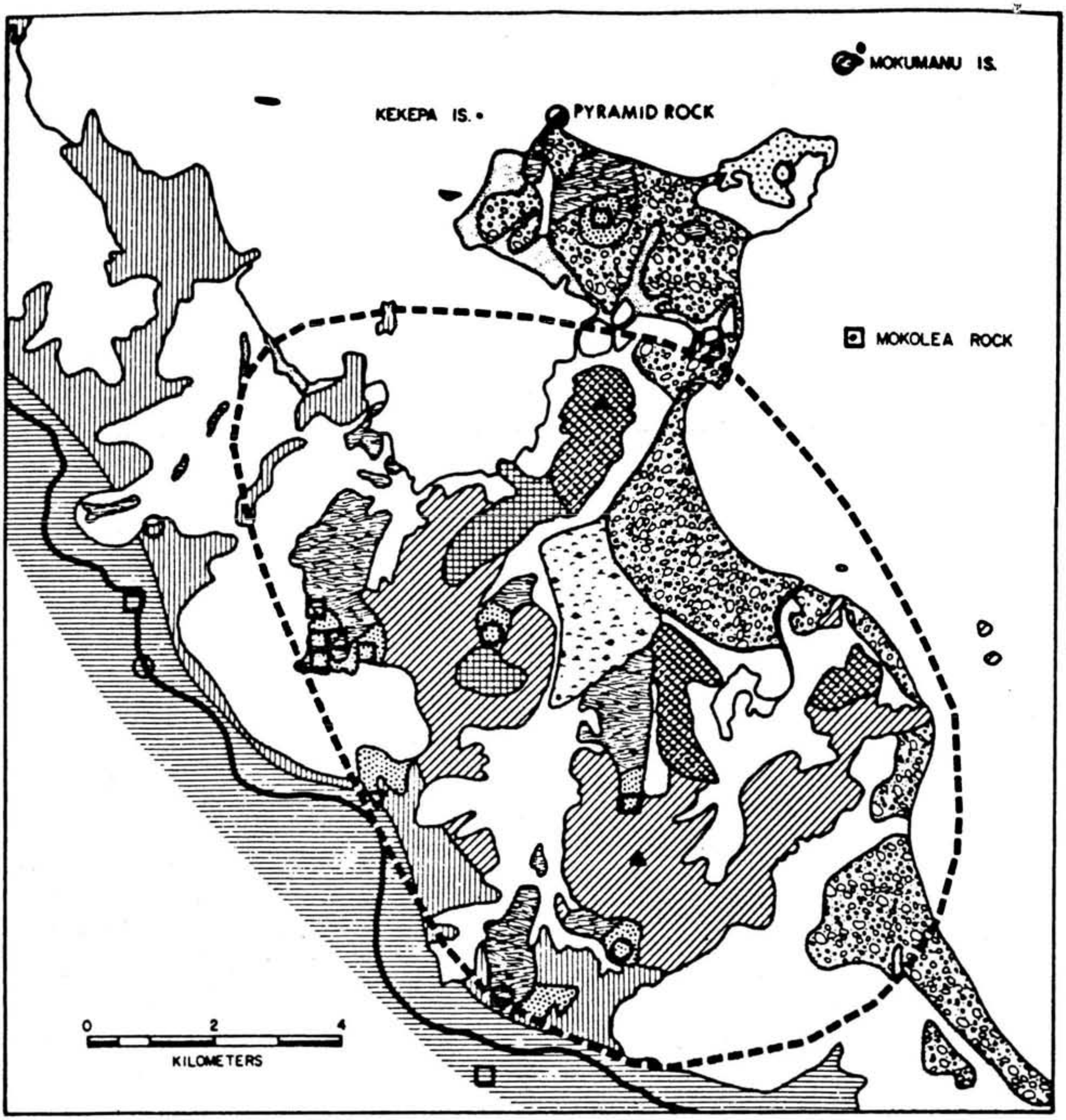


Fig. 12. Map of the detailed geology of Mokapu Peninsula and adjacent area (Oahu is.). Heavy broken line denotes the inferred boundaries of Koolau caldera; solid triangles designate topographic reference points. (From Cox *et al.*, 1982a.) Legend on p. 453.

validate the data set acquired during the preliminary assessment as well as to characterize any confirmed thermal resource.

West Maui Volcano

West Maui is the older of the two volcanoes forming the island of Maui. The bulk of the West Maui shield was formed between 1.15 and 1.3 My ago; post-erosional activity emplaced four small cinder cones along the southwest coastal plain over a period from approximately 70,000 years to 20,000 years before present (McDougall, 1964; Macdonald and Abbott, 1970).

The structure of the West Maui shield differs from that of most other Hawaiian volcanoes; the northwest and southeast rift systems form broad cones of dikes radiating out from the central caldera complex and are much less well-defined than is typically found in Hawaii.

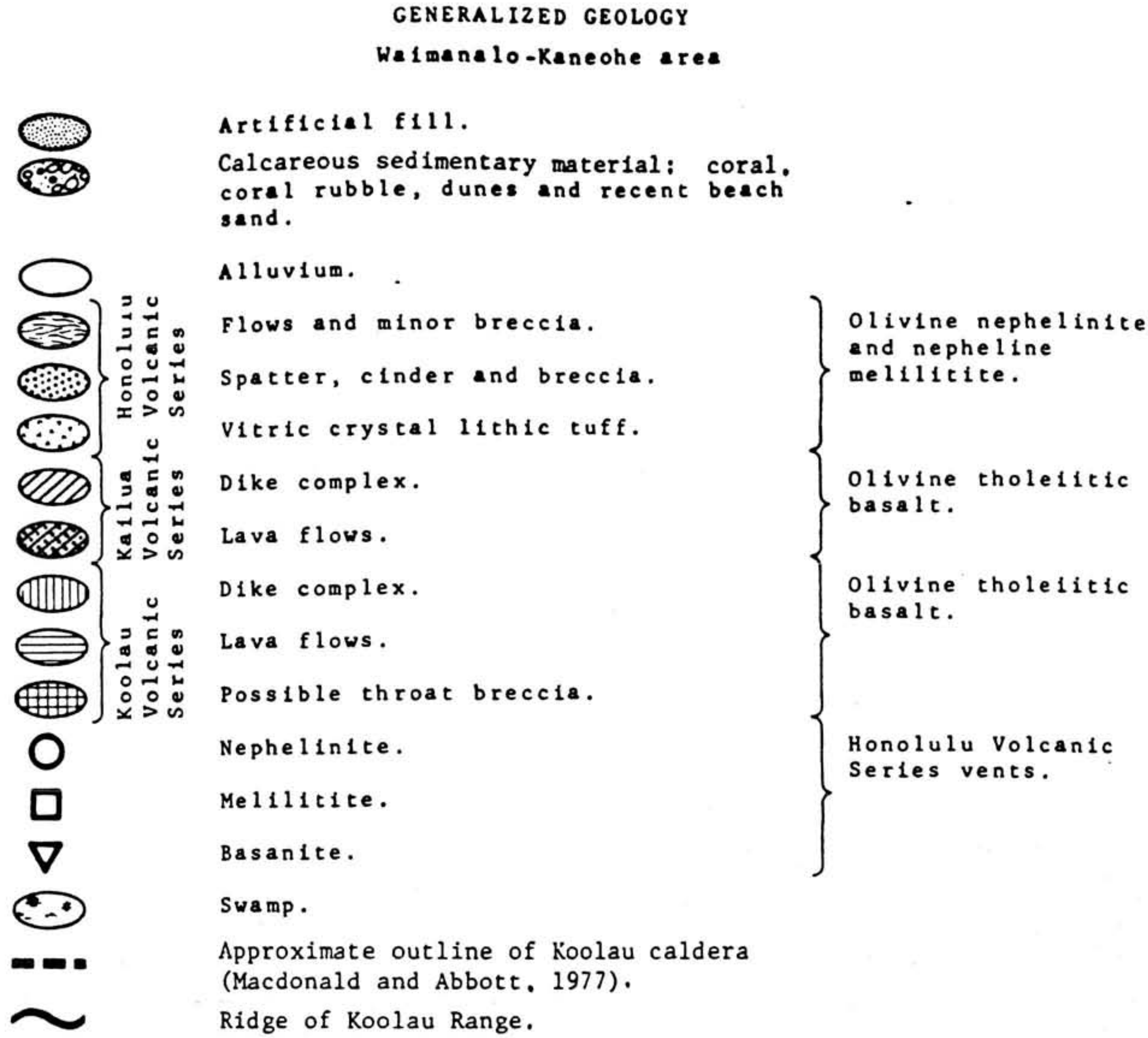


Fig. 12. Legend.

Recent structural and age studies of the southeast rift indicate that there was a migration of this system from a southeasterly strike to a southwesterly strike (Diller, 1982). This migration was inferred to be the result of changes in the regional stress field brought about by the growth of the adjacent Haleakala shield.

Three areas on West Maui were identified as having some potential as a geothermal resource: (1) The Olowalu-Ukumehame Canyon area on the south-west coast and adjacent to the southeast rift system of West Maui volcano, (2) Lahaina, near the site of several post-erosional vents, and (3) Honokowai, adjacent to the northwest rift zone of West Maui.

Although all three areas were identified on the basis of groundwater temperature or chemistry anomalies, the presence of a warm water source with a confirmed temperature of 30°C at the mouth of Ukumehame Canyon indicated that this area had the greatest potential of the three identified.

Olowalu-Ukumehame Canyon

Because the Olowalu-Ukumehame Canyon site was considered to have the highest potential as a geothermal resource on West Maui, the major field survey program concentrated on this area. Extensive geologic mapping was conducted throughout both canyons, geophysical soundings were performed within the valleys and along alluvial fans at the valley mouths, and groundwater chemistry studies were performed on all identified water sources within the area.

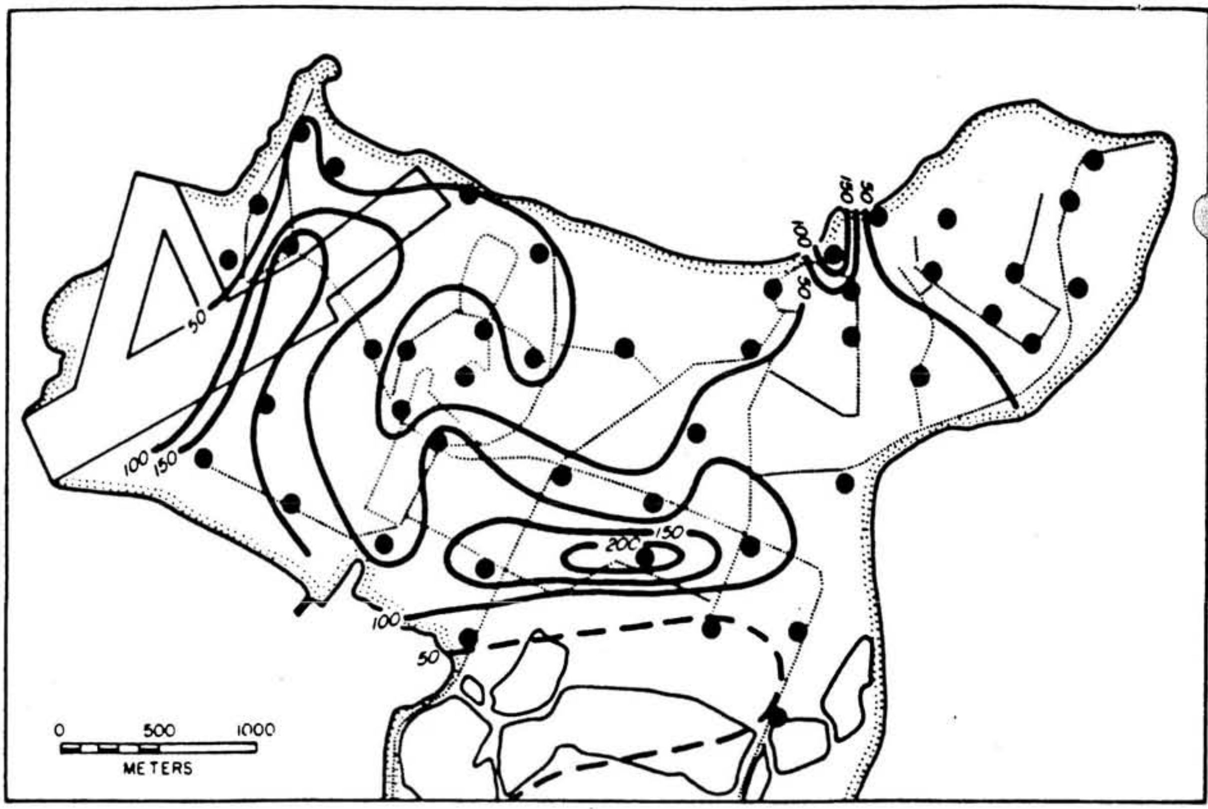


Fig. 13. Map of soil mercury concentrations found on Mokapu Peninsula (Oahu is.). Contour intervals are 50 parts per billion (ppb). Solid circles indicate sample locations. (From Cox *et al.*, 1982a.)

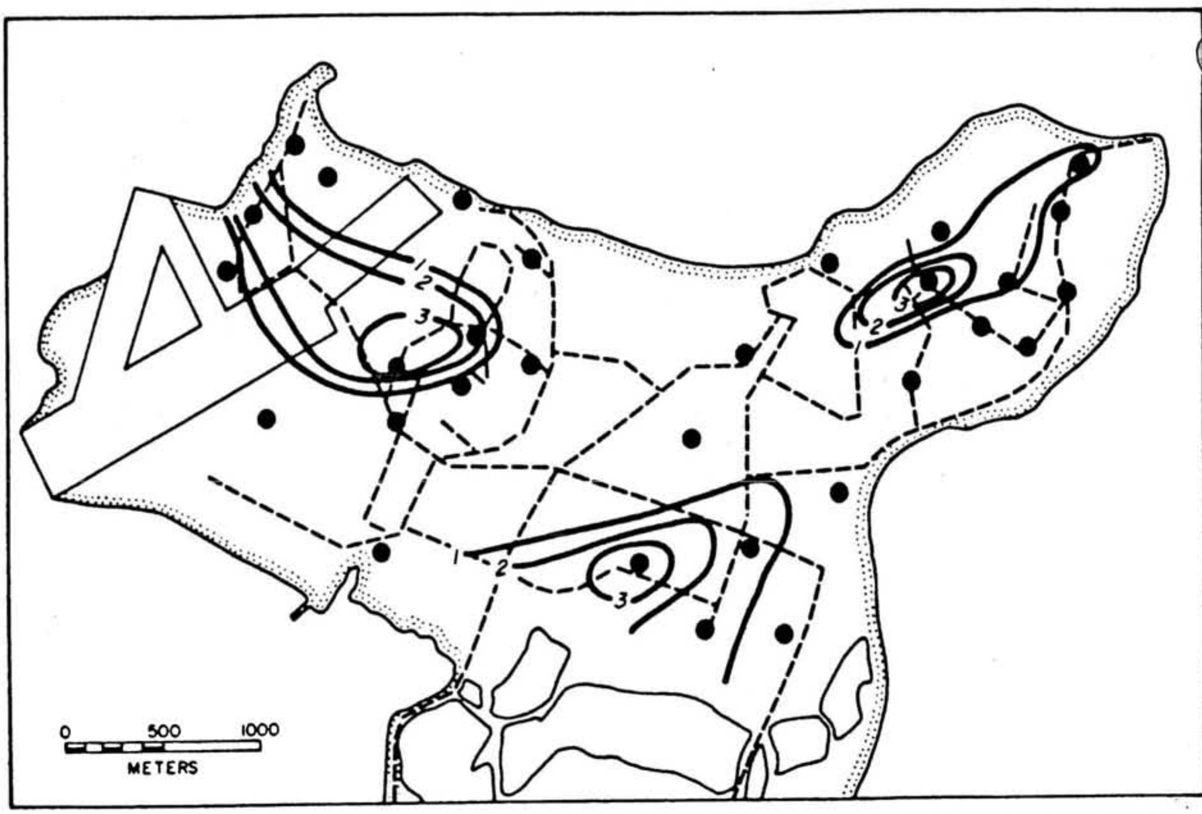


Fig. 14. Map of soil radon emanometry on Mokapu Peninsula (Oahu is.). Units are presented as field ra[illegible] concentration divided by the background levels found for the soil type in each area. Solid circles indicate sa[illegible] locations. (From Cox *et al.*, 1982a.)

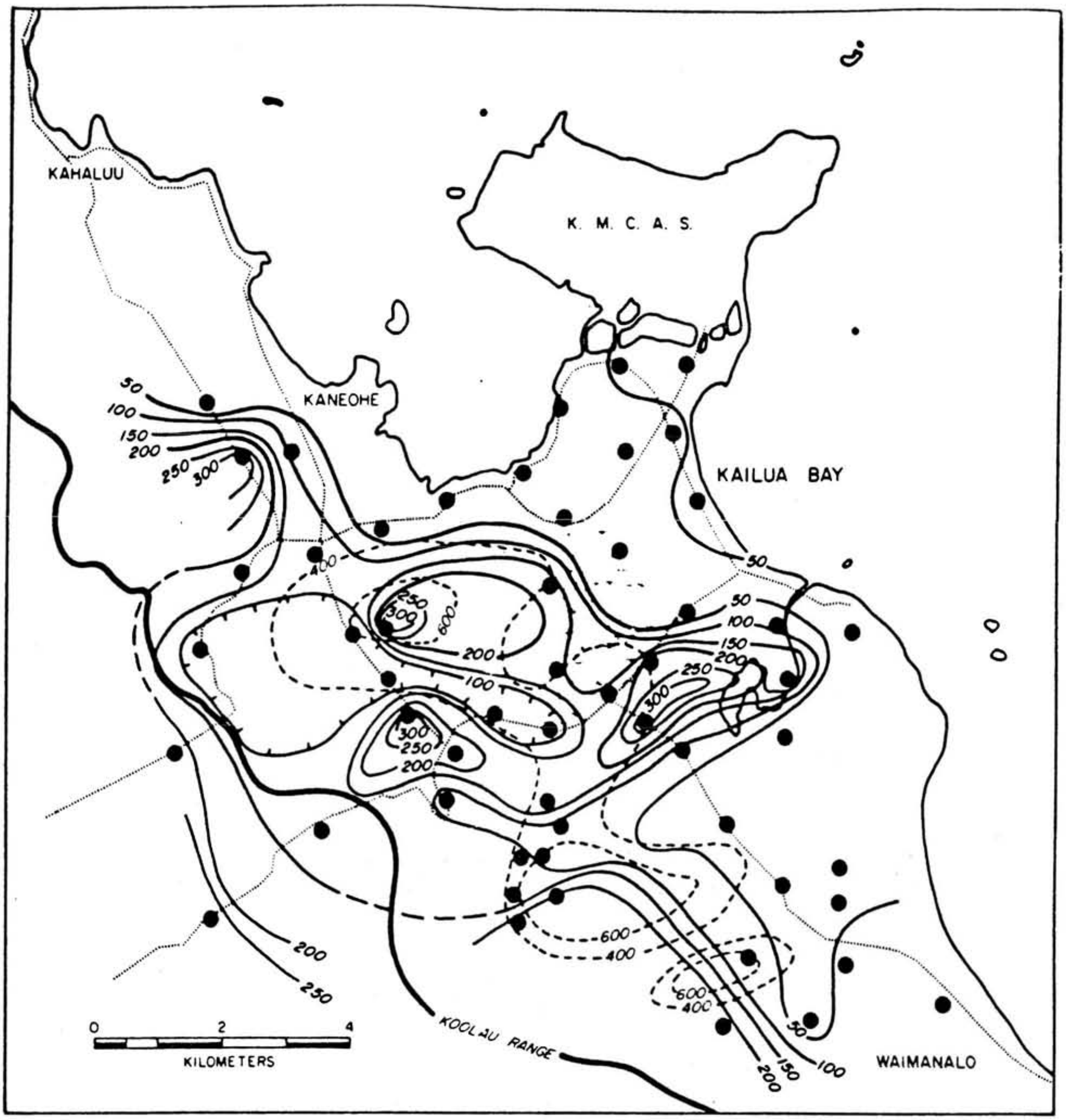


Fig. 15. Distribution of soil mercury concentrations in the Waimanalo-Kaneohe area (Oahu is.). Solid circles correspond to sample locations and contour lines are in 50 ppb increments. The lighter dashed contour lines refer to earlier published data. (From Cox *et al.*, 1982a.)

Geological mapping. The Olowalu and Ukumehame Canyons are located adjacent to and between the traces of the older southeast and the younger southwest rift zones of West Maui (Fig. 20). Geologic mapping (Diller, 1982) in this area has identified several trachitic and alkalic dikes, plugs, and vents within the area bounded by the canyons (Fig. 21). The frequency distribution of those dikes in the two rift zones was interpreted to indicate that eruptive activity occurred predominantly on the southeast rift zone during the early shield building stages of activity (approximately 1.32 My before present), but began to decline by 1.28 My b.p.; during the final stage of West Maui activity, at 1.16 My b.p., eruptive activity occurred primarily on the southwest rift system. The post-erosional activity on West Maui does not appear to be structurally related to any of the identified rift systems and hence the location of these vents provides little structural information of use in identifying a potential thermal resource.

Table 2. Chemical analyses of groundwater, Waimanalo-Kaneohe area, Oahu island

Fig. No.	Well No.	Name	pH	Temp. (°C)	Na	K	Ca	Mg	Cl	F	SO_4	$HCO_3 + CO_3$	SiO_2	Fe	Mn	Cl/Mg	Depth (m) well/water	Date	Elev. (m)
A	2750-02	Kahaluu Well	7.6	–	(27.9)		5.0	8.1	36.0	–	8.2	105.	19.8	0.2	–	4.4	– –	1937	–
B	2550-01	T-64	6.2	22.5	13.0	0.6	6.6	4.3	17.0	0.	3.4	43.	30.0	0.01	0.005	4.0	– –	1975	–
C	2448-01		7.7	–	(10.7)		6.5	4.6	14.0	0.1	8.2	46.	2.0	<0.1	<0.1	3.0	– –	1961	–
D	2348-02	Kuou Well I	7.5	–	(10.2)		23.0	6.7	20.0	0.1	7.2	71.	24.0	<0.1	0.	3.0	– –	1953	–
E	2246-01	Kahanaiki Well	7.6	–	(28.9)		27.9	9.5	30.0	0.3	18.4	68.	41.6	0.1	0.	3.2	– –	1953	–
F	2245-01	Training Schl. Well	7.0	–	(14.6)		13.7	11.8	37.0	0.2	11.2	93.	20.4	0.1	-	3.1	– –	1958	–
G	2142-03	Bellows A.F.B.	–	26.1	–	–	–	–	–	–	–	–	–	–	–	–	12.5/2.2	1962	6.1
H	2043-01	Waimanalo 408	7.3	30.0	28.0	1.1	14.0	2.8	25.0	0.1	5.4	84.	22.0	–	–	8.9	163.7/9.6	1970	7.9
I	2043-02	Waimanalo 420	6.9	25.0	36.0	1.0	12.0	6.8	27.0	0.05	10.0	148.	35.6	0.3	0.03	4.0	85.3/8.8	1971	43.3
J	2042-05	Waimanalo 420	–	30.0	–	–	–	–	–	–	–	–	–	–	–	–	137.2/ –	1966	–
K	2042-13	Waimanalo 420-1A	7.4	25.0	920.0	36.0	150.0	110.0	1700.0	0.2	220.0	224.	26.0	0.	0.01	15.5	48.8/ –	1975	15.2
L		C&C Waimanalo	8.0	–	(15.4)		16.3	6.3	18.0	0.1	8.7	37.0	12.0	0.1	0.	2.9	– –	1953	–
M		Haiku Tunnel	–	–	(12.4)		5.7	2.4	14.0	0.1	3.3	39.0	23.2	0.3	0.	5.8	– –	1948	–
N		Plantation Waimanalo	7.9	–	(13.4)		17.2	7.0	22.0	0.1	8.7	42.0	22.4	0.1	0.	3.1	– –	1953	–
O	Pond No. 1	N.E. Nuupia Pond	–	–	12534.	400.	407.	1432.	19110.	–	2433.	–	3.0	–	–	13.3	– –	1981	0.
P	Pond No. 2	Halekou Pond	–	–	9250.	400.	407.	1412.	19412.	–	2433.	–	2.9	–	–	13.8	– –	1981	0.
Q	Pond No. 3	Nuupia Pond	–	–	10566.	429.	423.	1366.	18809.	–	2257.	–	2.9	–	–	13.8	– –	1981	0.
R	Pond No. 4	Kaluapuhi Pond	–	–	13684.	588.	404.	1822.	25498.	–	3227.	–	3.5	–	–	14.0	– –	1981	0.

Source of data: U.S. Geological Survey, Hawaii—B, G, H, K.
Hawaii Dept. of Health—A, C, D, E, F, I, L, M, N.
Macdonald, 1973—J.

Analyses in parts per million (ppm).

( ) = Na + K.

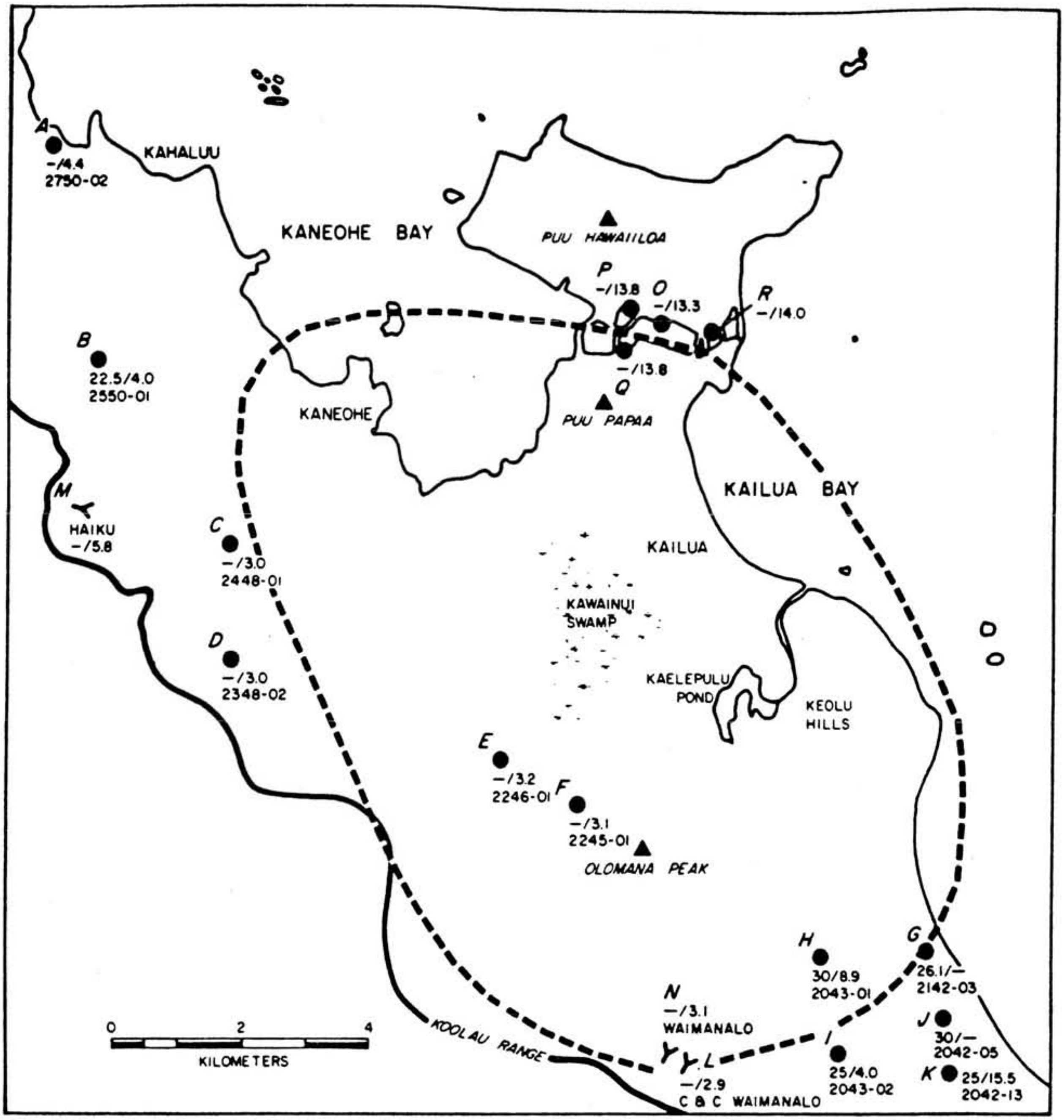


Fig. 16. Location of groundwater sources for which water chemistry has been assessed, Oahu island. Solid circles correspond to wells, "Y's" denote tunnels and solid triangles are topographic reference points. The heavy dashed line corresponds to the inferred caldera boundaries and the heavy solid line to the crest of the Koolau Range. The numbers presented adjacent to the well locations are as follows: left = temperature, right = Cl/Mg ratio, and the lower number is the well identification number. (From Cox *et al.*, 1982a.)

The frequency of dikes present in the Olowalu and Ukumehame Canyons was also used to identify the location of the caldera boundaries at the head of these valleys. The dike density data acquired indicated that the caldera boundary faults were located approximately 6 km from the mouth of Olowalu Canyon and approximately 4 km from the Ukumehame Canyon mouth.

Geochemical surveys. Soil mercury concentration and radon emanometry surveys were conducted along the stream beds in both Olowalu and Ukumehame Canyons and on the coastal alluvial fans (Cox and Cuff, 1981a). The results of these surveys indicated that a few minor anomalies might be present. However, the extreme topographic relief in the area did not permit

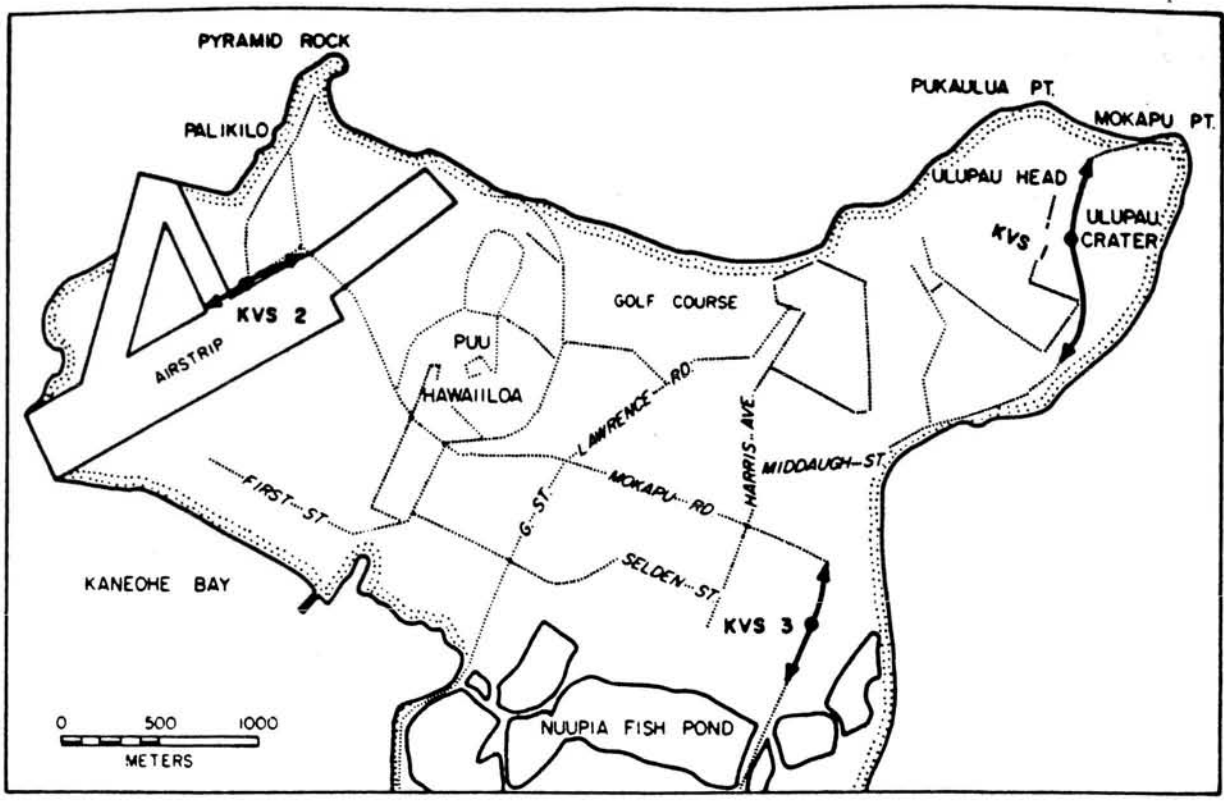


Fig. 17. Map of Mokapu Peninsula (Oahu is.) showing the locations of vertical electrical soundings. (From Cox *et al.*, 1982a.)

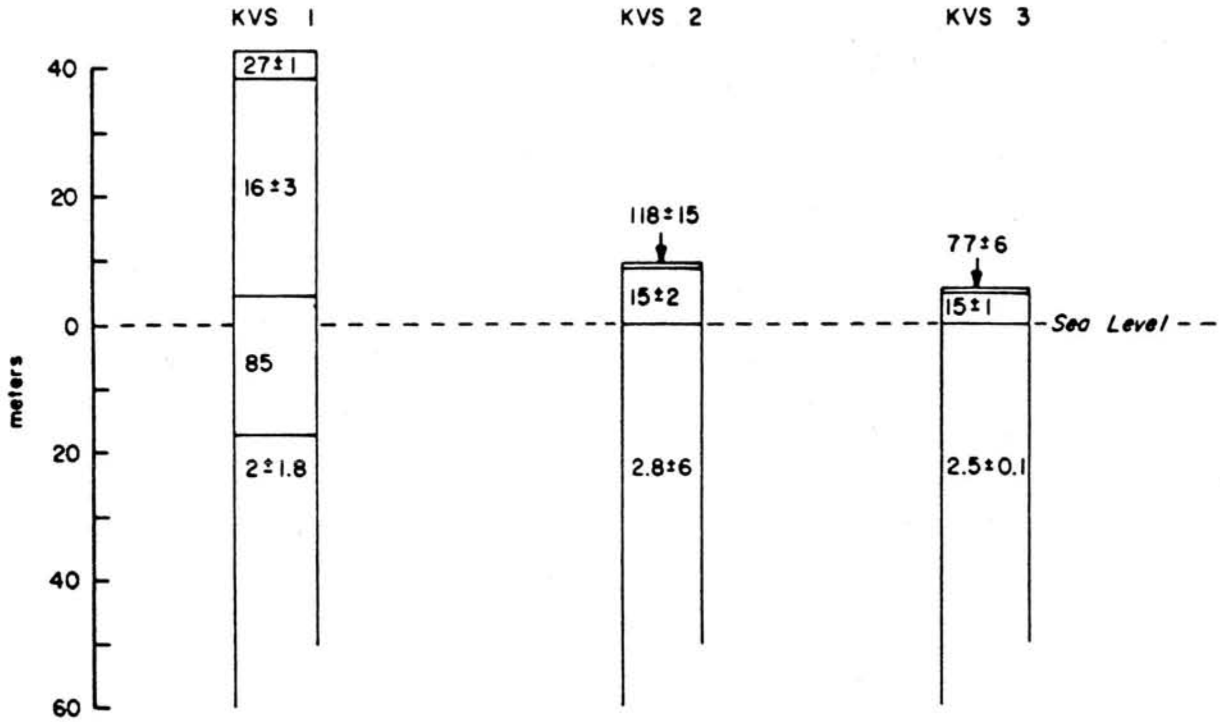


Fig. 18. Interpreted resistivity sections for three soundings conducted on Mokapu Peninsula, Oahu island, ohm·m. (From Cox *et al.*, 1982a.)

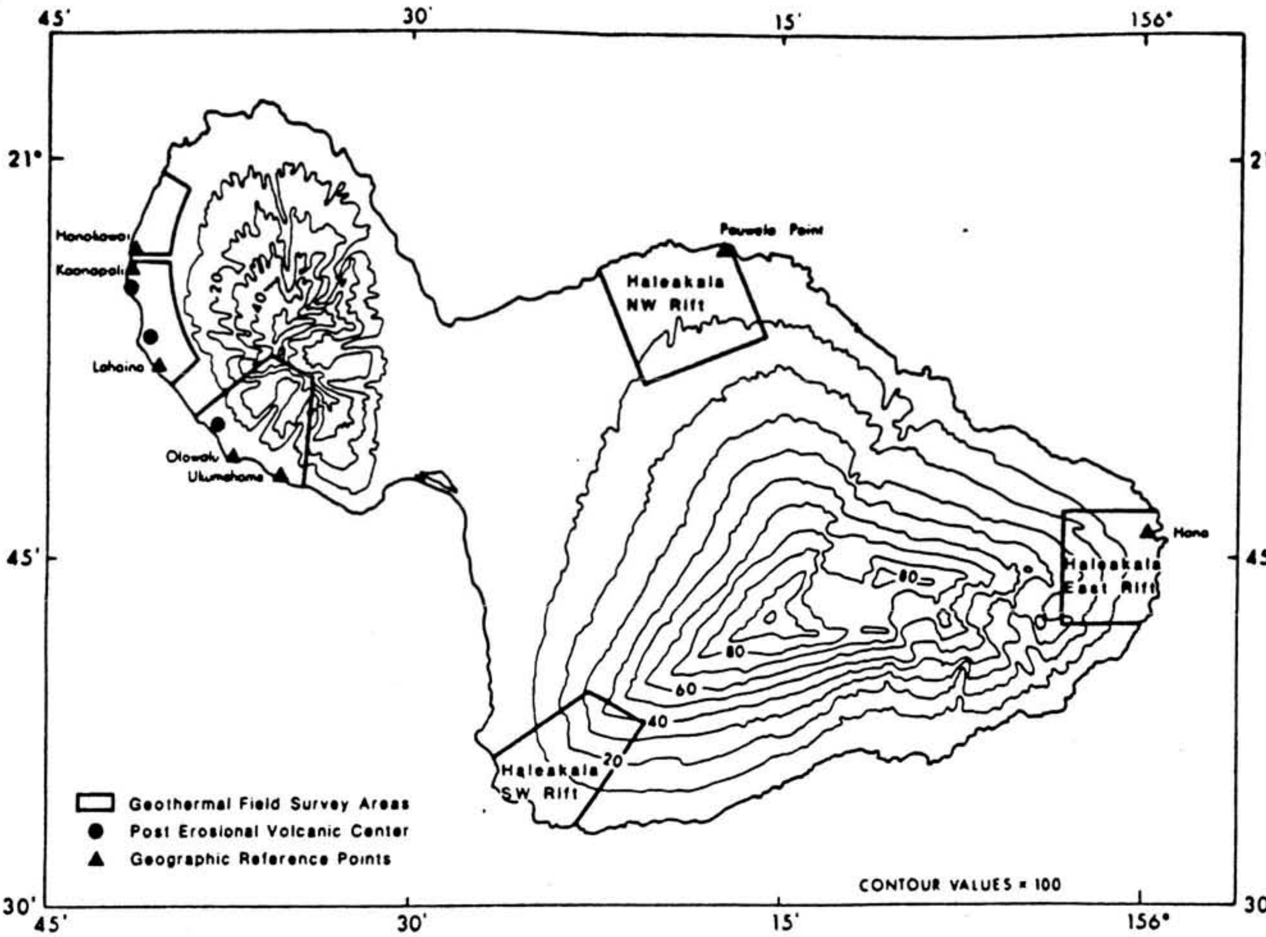


Fig. 19. Map of the island of Maui showing identified Potential Geothermal Resource Areas and the locations of subsequent field survey areas.

sufficient coverage of the area to allow any firm conclusions to be drawn from the small data set generated.

A preliminary groundwater survey in the area confirmed the presence of unusually warm groundwater (33°C) in a tunnel at the mouth of Ukumehame Canyon. Chemical analysis of the water produced by this aquifer indicates that the chloride/magnesium ion ratio has been significantly altered by thermal processes. More recently, a hydrologic study was initiated that has sampled spring and stream waters along the entire length of both Olowalu and Ukumehame Canyons. Although this study is still in progress, the data acquired to the present (Table 3) has confirmed a second source of thermal fluids near the back of Olowalu Canyon. The chemistry of the fluids in this location are significantly different from those found at the mouth of Ukumehame Canyon, suggesting that the thermal sources for these two locations may not be identical. Further study will be required to interpret the presently available data. It is of note, however, that the tritium levels (K. Kennedy, pers. commun., 1983) present in both locations indicate a predominance of recent meteoric recharge. This would suggest that the temperature anomalies observed in these water sources are the result of either rapid circulation of high volumes of meteoric recharge through a low temperature reservoir, or the result of contamination of surface aquifers by much smaller volumes of higher temperature fluids from depth.

Geophysical surveys. Geophysical surveys in the Olowalu-Ukumehame area have been largely confined to Schlumberger resistivity soundings along the coastal fan and, to a limited

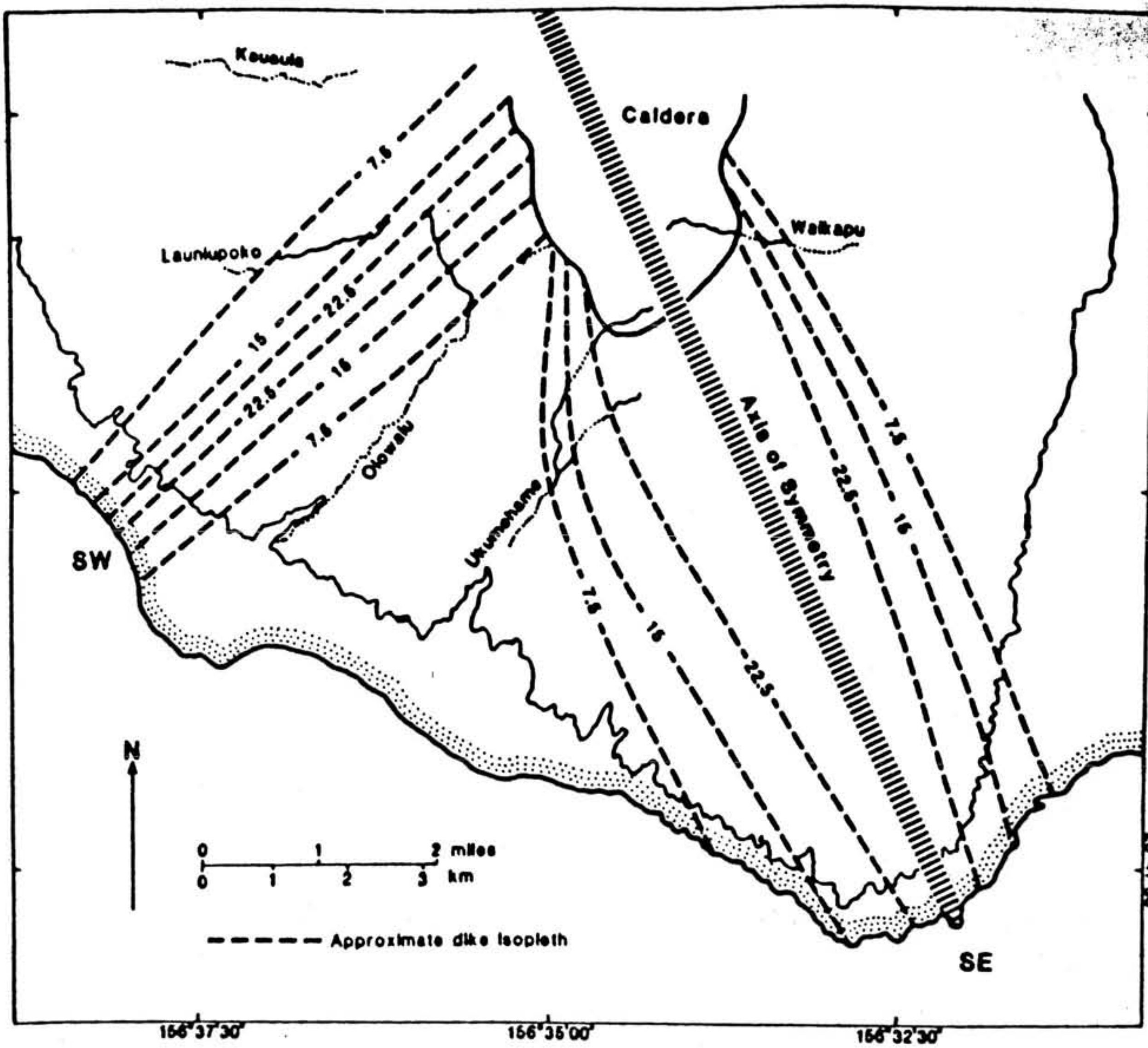


Fig. 20. Map of West Maui volcano. The broad hatched band corresponds to the axis of the southeast rift of West Maui, the solid line in upper center portion of figure corresponds to the inferred caldera boundaries, and the dotted lines to the stream beds located on the floors of each valley eroded into West Maui. The dashed lines are the contours of dike densities (in units of number of dikes per kilometer) observed in the valleys. (From Diller, 1982.)

extent, within the canyons (Mattice, 1981). An attempt was made to perform a deeper sensing, controlled-source electromagnetic sounding in this area as well, but difficulties in completing the sounding and in the subsequent data interpretation ultimately rendered the attempt unsuccessful.

A total of four Schlumberger soundings were completed successfully: one at the mouth and along the stream bed of each canyon (Fig. 22). The results of these surveys (Fig. 23) clearly detected the presence of unusually low-resistivity layers at depths corresponding to the local groundwater table and underlying basal aquifers. These low-resistivity layers were interpreted to be the result of a warm freshwater aquifer overlying warm seawater. Estimates of the temperatures of the fluids present ranged from a maximum of 322°C at a basalt porosity of 10% to 43°C at a basalt porosity of 30% (Mattice and Lienert, 1980; Mattice, 1981). The thickness of the warm water layer in this area was estimated to be approximately 700 m.

An attempt was made to perform a controlled-source electromagnetic sounding in an effort to detect the heat source for the identified thermal anomalies present in this area. The extremely

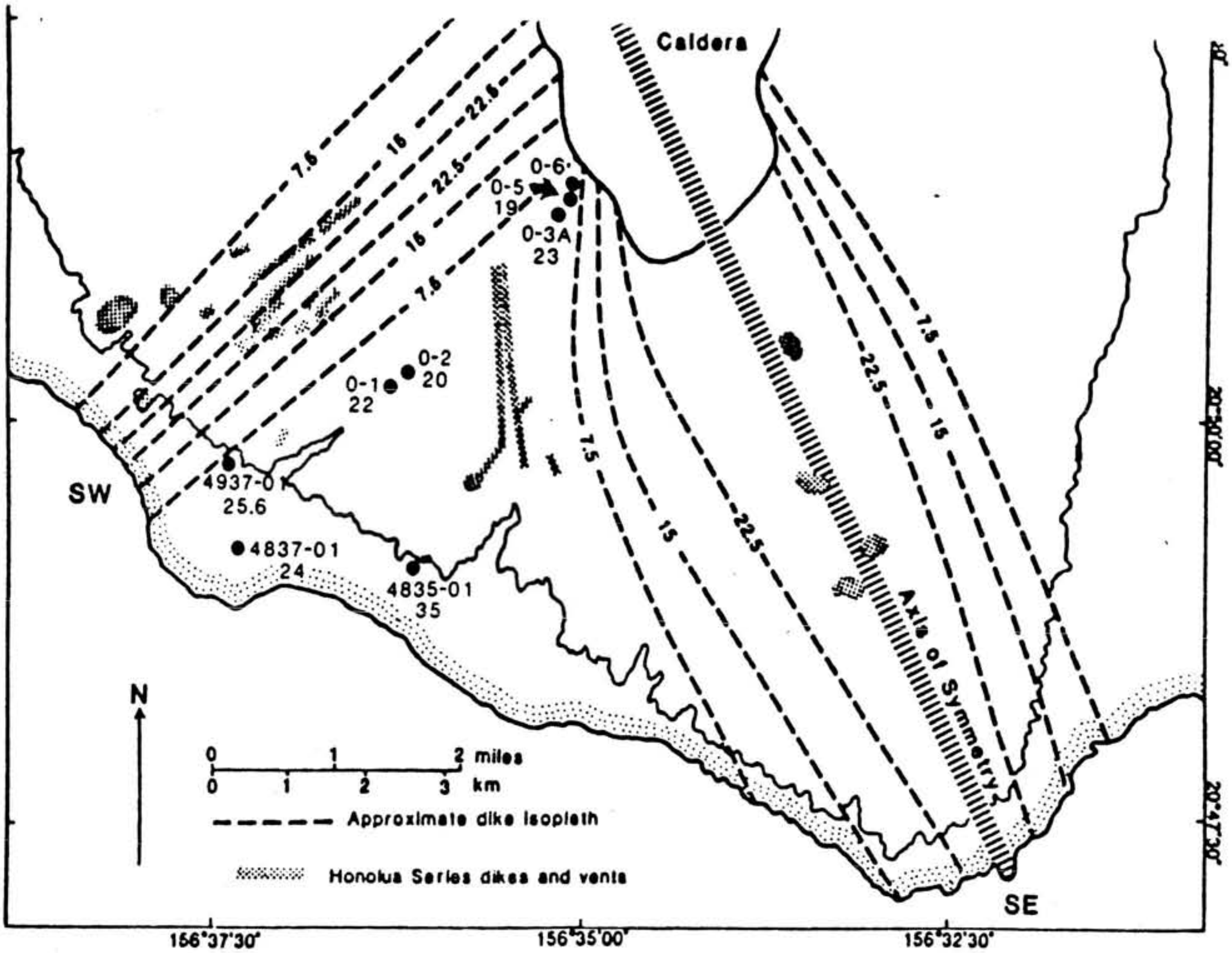


Fig. 21. Map of the southeastern flank of West Maui showing locations of late-stage Honolua series dikes and vents located on West Maui volcano. The solid circles denote groundwater well and spring locations: the upper number corresponds to the identification code number and the lower number corresponds to the temperature in °C measured at each well. (Modified from Diller, 1982.)

steep slopes of the canyon walls restricted the location of the transmitter to a jeep road on the ridge line above Ukumehame Canyon. Soundings were made from this location, but difficulties were encountered in data reduction due to the terrain corrections required. The uncertainties introduced by these corrections did not allow any conclusions to be drawn regarding the deeper subsurface resistivity structure in this area (Lienert, pers. commun., 1983).

Geothermal assessment. The geophysical and geochemical data acquired confirm the existence of at least a low- to moderate-temperature resource somewhere within the Olowalu-Ukumehame Canyon complex. Although further analysis will be required before the source of the thermal fluids can be uniquely identified, the data presently available suggest that it is probably located near the head of these canyons and could be associated with either the former magma chamber of West Maui volcano or smaller, late-stage intrusions on the southeastern flank of the volcano.

The probability of a low- to moderate-temperature resource existing in this area is estimated to be approximately 60 – 70%. The probability of a moderate- to high-temperature resource being present is considered to be much lower (10% or less) due to the age of the West Maui complex.

Table 3. Maui island. Groundwater chemistry in the Olowalu-Ukumehame study area

Sample location	pH	Temp. (°C)	Na	K	Ca	Mg	Cl	SO_4	HCO_3	SiO_2	Cl/Mg	(TU) ^3H	Depth (m) well	Elev. (m)	Date
0-1	8.5	22	25.6	2.1	4.9	4.2	29.7	20.2	153	57.7	7.0	5.2	–	–	7/83
0-2	7.8	20	36.9	2.7	9.2	8.3	38.9	18.8	238	58.6	4.7	4.2	–	–	7/83
0-3A	7.9	23	43.3	1.8	187.2	14.7	8.9	628.2	170	44.4	0.6	9.2	–	157.9	7/83
0-5	7.8	19	9.2	0.6	7.9	3.6	9.1	10.4	136	27.1	2.5	8.4	–	–	7/83
0-6	8.0	–	15.0	0.3	13.5	9.01	14.9	13.2	170	47.7	1.7	6.1	–	–	7/83
4837-01	7.4	24	263.7	7.6	40.7	34.7	339.3	63.7	408	46.9	9.8	24.5	27.7	15.2	7/83
4835-01	7.8	35	202.2	28.2	53.3	18.8	393.4	50.6	340	51.2	20.9	23.4	13.4	7.3	7/83
4937-01	7.1	25.6	255.0	11.9	112.0	78.0	669.0	76.0	141	73.5	8.6		91.5	50.3	7/83

01-06 are spring water samples.
4837-01 – 4937-01 are U.S.G.S. well locations.
Concentrations are in mg/kg.
See Fig. 21 for spring and well locations.

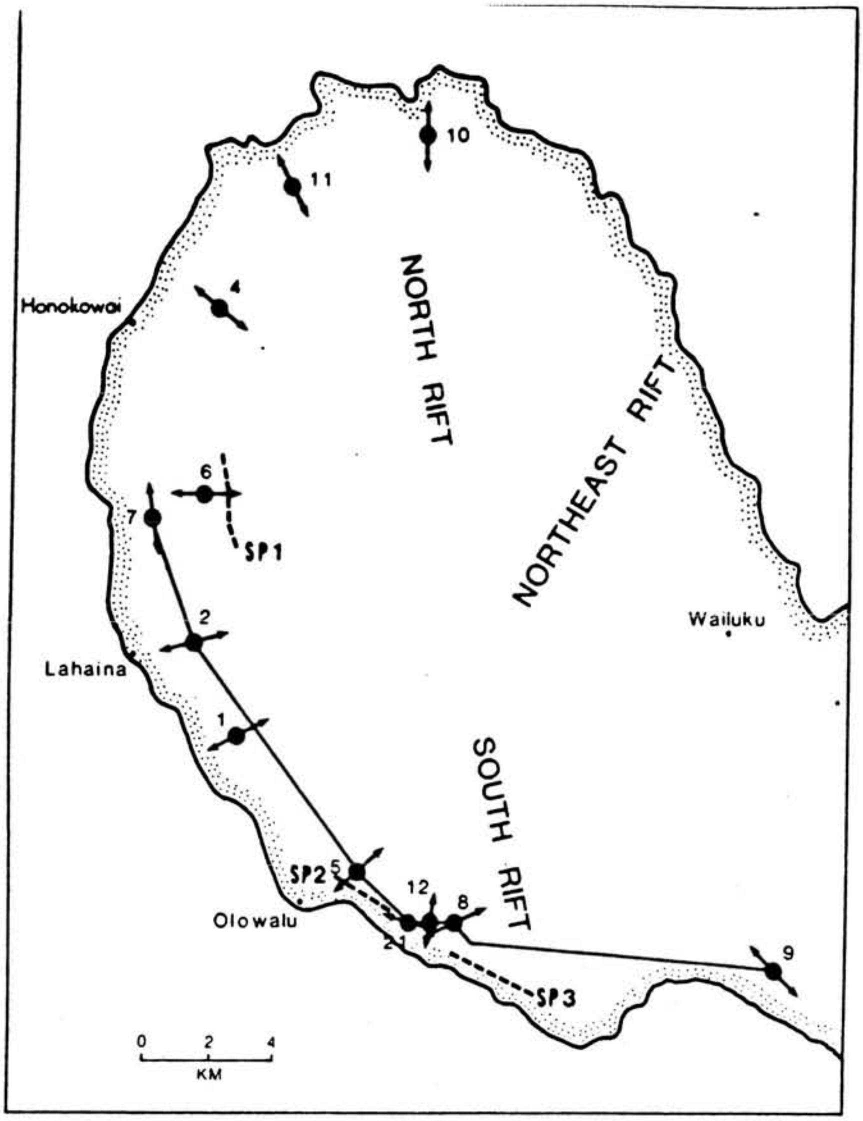


Fig. 22. Map of West Maui volcano showing the locations of Schlumberger soundings and self-potential traverses in the Olowalu-Ukumehame Canyon, Lahaina-Kaanapali, and Honokowai survey areas. Heavy solid lines correspond to Schlumberger soundings and dashed lines to self-potential traverses. (From Mattice, 1981.)

Lahaina-Kaanapali

The Lahaina-Kaanapali survey area is located to the northwest of Olowalu Canyon on a broad alluvial plain. Although the two post-erosional vents Puu Laina and Kekaa Point have been identified within the survey area, there does not appear to be any relationship between these vents and the rift zones of West Maui volcano.

Lahaina-Kaanapali was identified as a PGRA on the basis of reported water temperature and water chemistry anomalies. Field surveys conducted during the current assessment effort consisted of Schlumberger soundings, limited soil mercury and radon emanometry studies, and a survey of accessible groundwater sources.

Geophysical surveys. Four Schlumberger soundings were performed along the coastal strip adjacent to Lahaina town (Fig. 22). Three of the four soundings were able to detect a moderate-to low-resistivity basement that was interpreted to be basalt saturated with seawater at 20°C (Mattice, 1981). None of the resistivity sounding data in this area indicated subsurface resistivities lower than could be accounted for by local ambient temperatures (Mattice and Lienert, 1980).

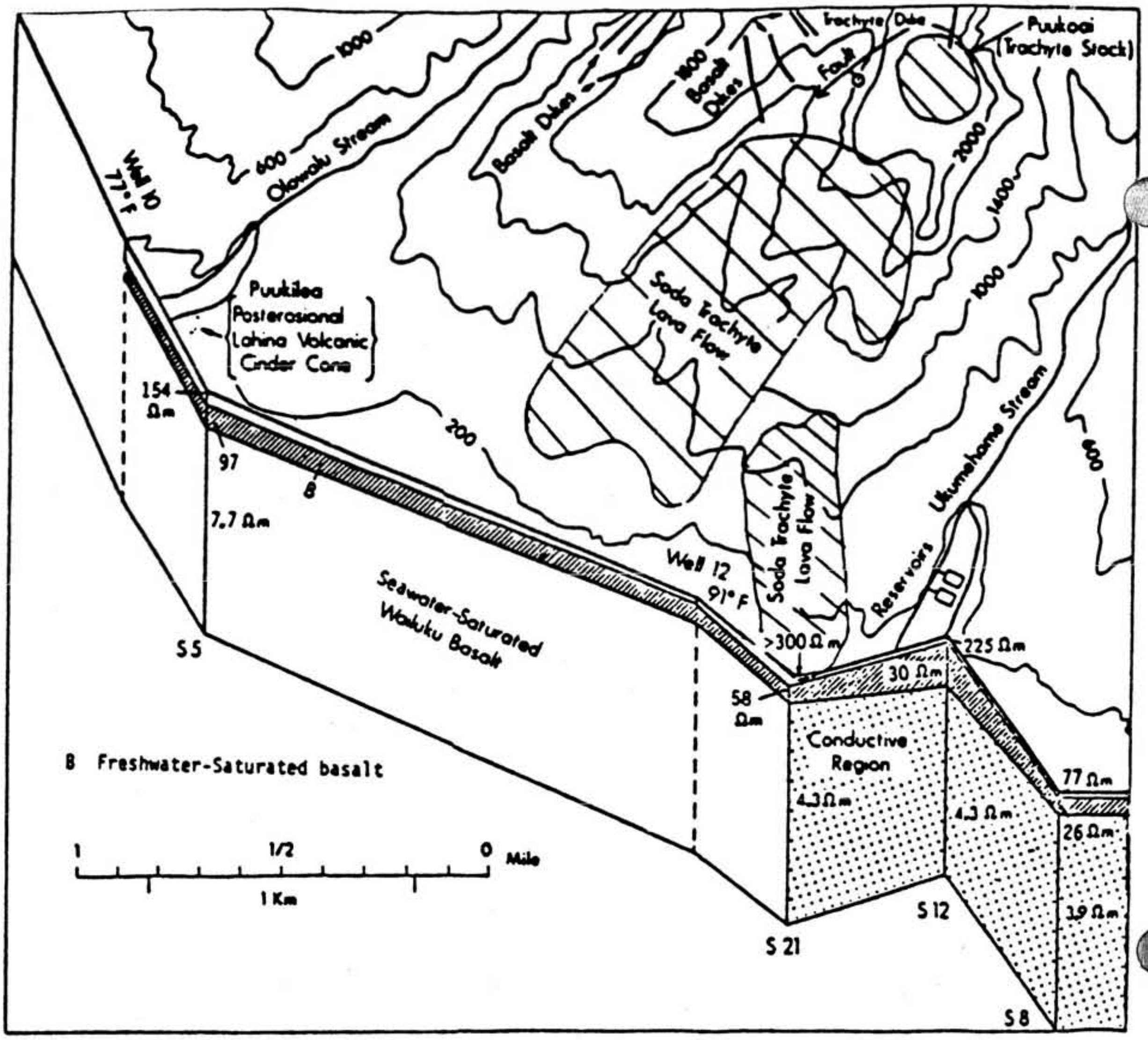


Fig. 23. Interpreted resistivity structure beneath West Maui volcano. Conductive region is believed to correspond to warm water-saturated basalt beneath Olowalu and Ukumehame Canyons. (From Mattice, 1981.)

Geochemical surveys. The soil mercury concentration and radon emanometry patterns observed for the Lahaina prospect were similar to those found in Olowalu. Several localized zones of high mercury concentration or enhanced radon emanation were observed, but showed little relationship to each other or to the recognized geologic structure in the area. The data were interpreted to suggest that there might be a small thermal anomaly to the northeast of the survey area, but the probability of this being the case was considered to be very low.

Groundwater temperature and chemistry surveys were similarly unable to identify any detectable thermal influence on the basal groundwaters. Silica concentrations and water temperatures (Table 4) were within the normal range expected for basal groundwaters receiving a limited amount of irrigation return water; chloride/magnesium ratios ranged downward from normal seawater values.

Geothermal assessment. The virtual absence of any substantial geochemical or geophysical indication of higher than normal subsurface temperatures around the Lahaina-Kaanapali area suggests that the probability of even a low- to moderate-temperature geothermal resource existing in this area is near zero.

Table 4. Groundwater chemical analyses in the Lahaina-Kaanapali survey area, Maui island

Sample location	pH	Temp. (°C)	Na	K	Ca	Mg	Cl	SO_4	HCO_3	SiO_2	Cl/Mg	Depth	Elev.	Date
5240-01	7.2	26.82	465	17.0	123	119	1030	144	194	64.4	8.6	11.9	10.4	1978
5240-02			672	22.0	134	140	1360	200		67.4	9.7	9.4	9.1	1978
5240-03	7.2	24.93	406	16.2	164	132	1040	134	246	5.9	7.9	9.4	9.1	1978
5339-04	8.0	20.30	188	5.8	57	37	403	56	68	50.0	10.9	228.3	199.4	1978
5340-01	7.4	25.20	413	13.4	166	174	1180	240	150	51.4	6.8	8.2	7.9	1978
5340-02	7.4	23.65	536	19.2	93	102	1070	157	91	57.3	10.5	98.5	98.2	1978
5540-01	7.7	21.79	320	15.0	36	62	62	82	146	66.6	1.0	143.9	135.4	1978
5641-01	7.1	22.85	864	30.0	94	149	1530	210	172	68.0	10.3	8.5	8.2	1978
5641-02	7.7	22.68	773	30.2	88	128	1470	208		59.6	11.5	19.8	19.8	1978
5840-01	7.24	21.42	177	8.5	12.4	20	291	10	88	8.7	14.0	83.5	262.2	1978

Concentrations are in mg/kg.
Well depths and elevations are given in meters.
See Fig. 24 for well locations.

Honokowai

Honokowai is located on the northwestern flank of West Maui volcano and is adjacent to its northwest rift zone. This prospect was initially identified as a PGRA on the basis of several low-level groundwater geochemical anomalies (Thomas *et al.*, 1979). Since this area was not considered to have a high probability of possessing geothermal potential, only a limited set of geophysical and geochemical surveys were conducted in and around Honokawai.

Geophysical surveys. Three Schlumberger resistivity surveys were attempted on the alluvial plain around Honokowai (Fig. 22). Two of the soundings penetrated to a moderate-resistivity basement, interpreted to be seawater-saturated basalt, whereas the other sounding encountered a high-resistivity intermediate layer which could not be adequately penetrated to allow resolution of the basement resistivity (Mattice, 1981).

Geochemical surveys. Temperature and groundwater chemistry analyses were performed on three wells along the alluvial fan above Honokowai. Water temperatures were approximately 20°C and normal basal aquifer water chemistry was observed (Table 4).

Geothermal assessment. Even though the Honokowai prospect is located adjacent to the West Maui northwest rift zone, the apparent absence of significant thermally induced geophysical or geochemical anomalies indicates that the probability of geothermal energy potential existing in this area is probably less than 5%.

Haleakala Volcano

Haleakala is the younger and larger of the two volcanoes forming the island of Maui. Three major phases of eruptive activity have been recognized for Haleakala. The Honomanu phase formed the major part of the subaerial shield and is believed to have ended approximately 750,000 years ago (Macdonald and Abbott, 1970). The Kula Volcanic Series followed and spanned a period of approximately 250,000 years and was, in turn, followed by 400,000 years of quiescence. The final stage of activity was the Hana Volcanic Series that began 70,000 years ago and is currently underway; the most recent eruption of this series occurred in 1790 on the lower southwest rift of Haleakala (Macdonald and Abbott, 1970).

Structurally, Haleakala resembles most other Hawaiian volcanoes in its current post-erosional phase of activity. Two major rift zones extend outward from the summit to the east and southwest, and a third minor rift extends to the northwest. Geologic mapping on the Haleakala shield has found that the majority of the late-stage eruptive activity was restricted primarily to the east and southwest rift zones, whereas very few late-stage and no post-erosional vents are present on the northwest rift.

The preliminary assessment survey identified the lower portions of all three rift zones as PGRAs. Although relatively few geophysical or geothermal data were available for the east and southwest rift zones, the presence of geologically recent volcanic activity in these areas strongly suggested that a resource might be present. The northwest rift zone was identified on the basis of groundwater temperature and chemistry anomalies.

Haleakala northwest rift

The northwest rift zone of Haleakala, as noted above, has experienced only infrequent and scattered eruptive events during the later phases of the volcano's activity; fewer than a dozen Kula Volcanic Series vents have been identified on the lower northwest rift and more recent Hana Volcanic Series vents are entirely absent. The Kula Volcanic Series vents on this rift are believed to be approximately 400,000 to 800,000 years old (McDougall, 1964).

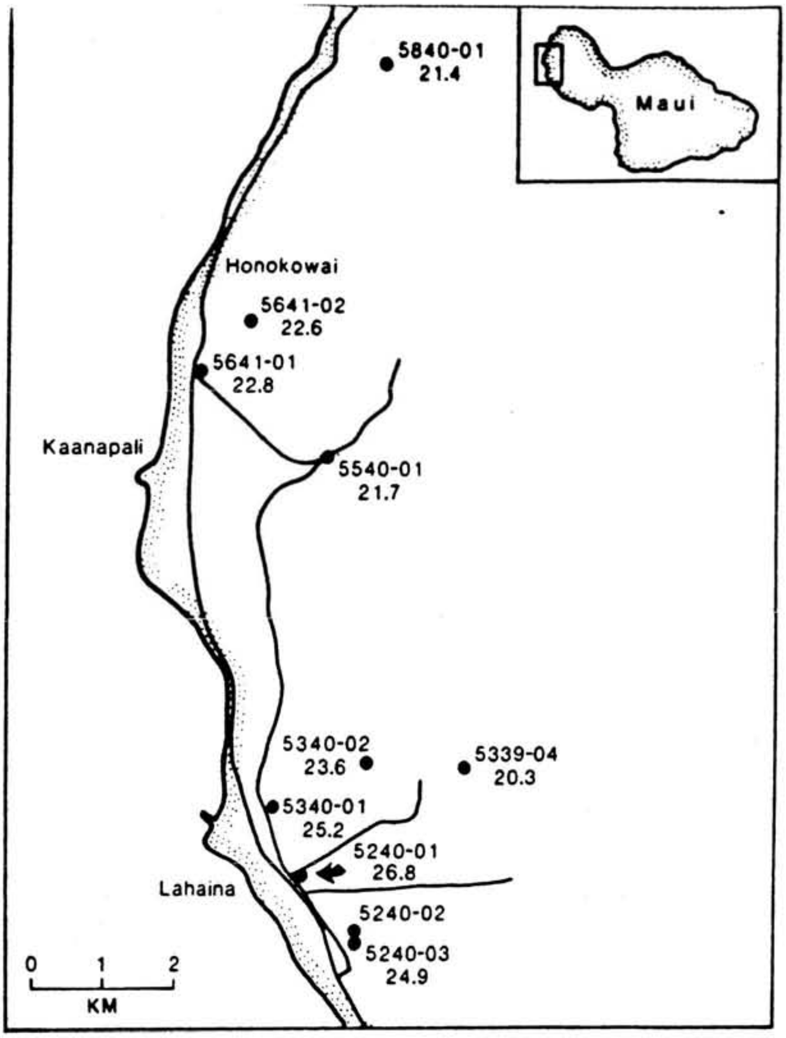


Fig. 24. Map of groundwater well locations in the Lahaina-Kaanapali survey area (Maui is.). The upper number refers to the well identification number; the lower number is the temperature in degrees Celsius measured at each well.

The field survey program on the northwest rift zone consisted of soil mercury and radon emanometry surveys, groundwater temperature and chemistry studies, Schlumberger resistivity soundings and self-potential profiles.

Geochemical surveys. Soil mercury and radon emanometry traverses were completed at several elevations across the trace of the northwest rift. Soil mercury levels generally indicated higher than average levels through a zone extending from the northeastern edge of the lower rift zone toward the southwest across the rift (Fig. 25); some locally very high values (greater than 800 ppb) were identified in two locations along this trend. The interpretation offered for the mercury data was that the high levels observed correspond to faulting within the rift zone and may indicate geothermal influences (Cox and Cuff, 1981b). The diversity of soil type and organic content within the survey area may, however, account for some of the variations observed.

Radon emanometry surveys indicated an elongate north/south zone of unusually high radon values adjacent to and east of the trace of the rift (Fig. 26). The zone appeared to terminate at Maliko Gulch which is believed to be a fault-produced feature. It is suggested that the anomalous radon emanation area is the result of enhanced ground gas permeability due to fault-induced fracturing (Cox and Cuff, 1981b). Thermal enhancement of ground gas movement may also play a part in the higher radon emission rates observed here.

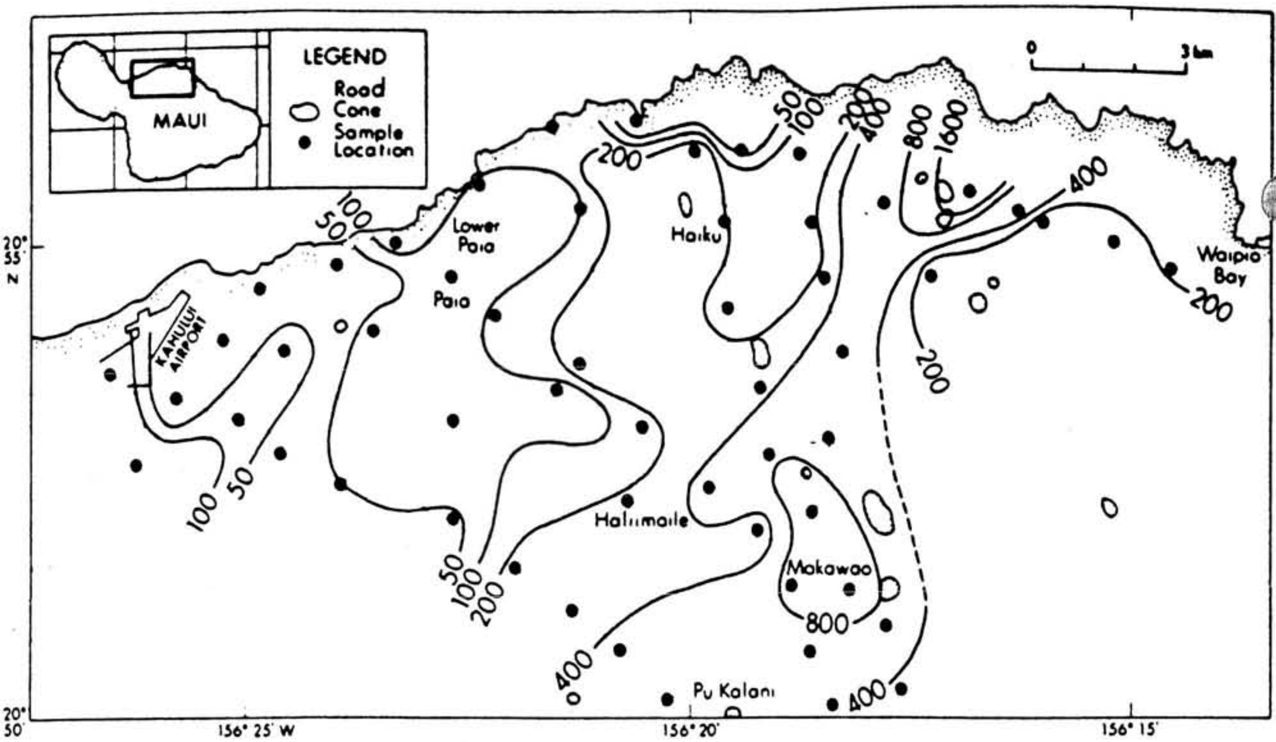


Fig. 25. Map of soil mercury concentrations on the lower northwest rift zone of Haleakala volcano (Maui is.). Units are in parts per billion (ppb) and are contoured geometrically. Dark lines are mercury concentration contours and dark dashed line is inferred mercury concentration contour. (From Cox and Cuff, 1981b).

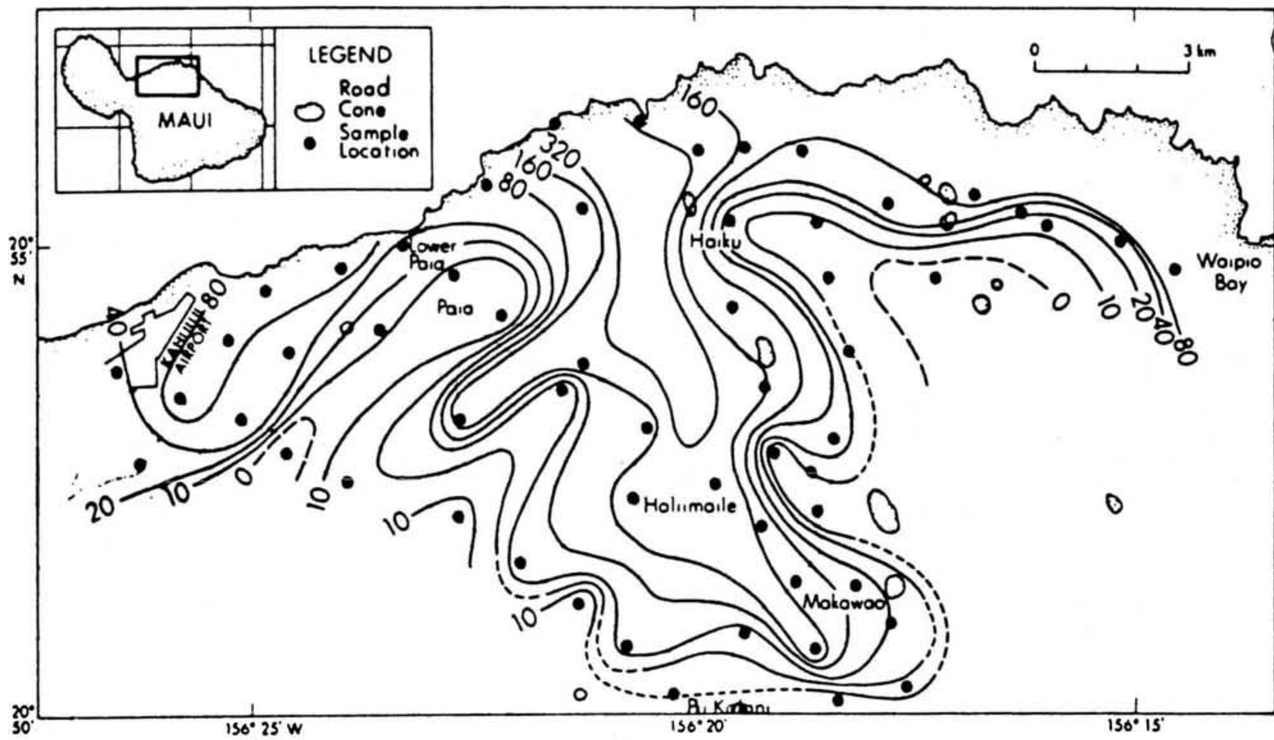


Fig. 26. Map of ground radon emanation results (Maui is.). Contours are in tracks per square centimeter per hour of exposure (× 100), corrected for soil background and contoured geometrically. Dark lines are radon concentration contours and dark dashed lines are inferred radon concentration contours. (From Cox and Cuff, 1981b.)

Groundwater temperature and water chemistry surveys were conducted in an effort to substantiate the earlier reported temperature and chemistry anomalies. Although the earlier data set was generally validated, additional data gathered tend to indicate that the anomalies observed are not of geothermal origin. Water temperatures measured ranged from 19 to 24°C (Table 5); the higher temperatures observed correspond to ash bed perched aquifers rather than basal groundwaters. The former sources also seem to account for most of the chloride/magnesium ion ratio anomalies as well. These results suggest that the ash bed perched aquifers are carrying local, low-elevation and hence warmer recharge that has undergone limited ion exchange with clays formed in the ash bed. Thus, the groundwater anomalies observed are not considered to be the result of geothermal influences.

Geophysical surveys. Four Schlumberger resistivity soundings were performed along the northeast rift: two were located within the trace of the rift and one each to the east and west of the rift (Fig. 28) (Mattice, 1981). All of the soundings were performed at elevations of less than 120 m above sea level. Three of the soundings—numbers 17, 18, and 19—were able to resolve subsurface layers corresponding to Kula and Honomanu Volcanic Series basalts saturated with cold freshwater and cold seawater. The fourth sounding—number 15—encountered a 200 m thick layer of lower than anticipated resistivity (the top of which was located at a depth of 20 m). This layer was interpreted to be a clay or alteration zone that was at ambient (low) groundwater temperatures (Mattice and Lienert, 1980; Mattice, 1981).

Three self-potential traverses were conducted across the northwest rift zone (Fig. 28) (Mattice and Kauahikaua, 1981): SP-4 at an elevation of approximately 100 m, SP-5 at an elevation ranging from 490 to 790 m, and SP-6 ranging from 1750 to 2070 m.

Traverse numbers 4 and 5 showed only minor irregularities (Fig. 29) that were attributed to cultural features such as culverts, or fence lines. Profile 6 (Fig. 30), although quite irregular, exhibited a distinctive negatively polarized spike near Puu Nianiau (a Kula series cinder cone) and also a broad positive feature over the trace of the rift zone. The negatively polarized spike was interpreted to be the result of a streaming potential within a zone of locally enhanced permeability associated with the Puu Nianiau eruptive vent. The source of the broadly polarized feature was considered to be somewhat more ambiguous; a thermoelectric effect was considered possible, however, the presence of a high-level, dike-confined artesian aquifer within the rift zone was suggested as an alternative source of the anomaly observed (Mattice and Kauahikaua, 1981).

Geothermal assessment. It is clear that several of the geochemical and geophysical evaluation techniques that were applied to the rift zone identified conditions outside the ranges normally expected. However, the absence of a spatial coincidence of the observed anomalies and the apparently conflicting interpretations possible for the data would suggest that the geochemical and geophysical variations detected on the northwest rift zone are not primarily the result of a geothermal system.

The probability of a low- to moderate-temperature resource existing on the northwest rift zone of Haleakala is estimated to be no greater than 10 – 20%. The probability of a moderate- to high-temperature resource being present is placed at less than 5%.

Haleakala southwest rift

The southwest rift zone is the site of the only historic eruption on the island of Maui. This eruption occurred in or about 1790 and produced approximately 27 million m^3 of lava from two vents located at altitudes of 472 m and 155 m a.s.l. (Macdonald and Abbott, 1970). This rift zone has clearly been one of the major foci of volcanism during the Kula and the Hana phases

Table 5. Groundwater chemistry from wells on the Haleakala Northwest Rift, Maui island

Sample location	pH	Temp. (°C)	Na	K	Ca	Mg	Cl	SO_4	HCO_3	SiO_2	Cl/Mg	Depth	Elev.	Date
5319-01		19.8	19	1.9	2.5	4.1	17.3	11.7			4.2	–	–	1979
5321-01	7.7	20.5	232	16	20.6	32.5	431	95	140	53	13.2	–	159.1	1979
5323-01	7.2	22.8	300	17	27.3	47.9	543	178	140	56	11.3	–	38.1	1979
5419-01		22.0	30		2.4	6.6	26.3	14.4			4.0	–	–	1979
5420-01	6.9	19.0	73	3.8	4.0	3.26	44.3	51.4	79	53.3	13.6	113.1	106.4	1979
5422-01		22.5	174	14.6	38.0	53	531	91.5			10.0	45.7	47.2	****
5422-02		21.2	175		25.5	33.3	316				9.5	–	89.9	1979
5423-01		23.2	360	23	42.6	56.4	706	120		99	12.5	–	5.5	1979
5423-02	7.2	23.5	840	40	73.2	123	1572	220	178	102	12.8	–	7.6	1979
5519-01		19.1	57	4.7	15.0	14.6	130	12.2			8.9	121.9	111.3	1979
5519-02		23.5	4.3	2.3	1.5	0.84	18.1	23.2		40.8	21.5	69.5	109.7	1978
5520-01		20.5	475	23	396.0	64.5	887	156			13.8	–	9.1	1979
5522-01	6.9	21.3	203	8.6	14.5	18	295	68	125	52	16.3	–	47.6	1979
5615-01		23.5	33	1.15	4.2	4.2	38.3	17.4			9.1	63.4	–	1979
5620-01		21.5	66	2	0.53	0.40	23.2	58.5			58.0	–	15.2	1979

Concentrations are in mg/kg.
Well depths and elevations are in meters.
See Fig. 27 for well locations.

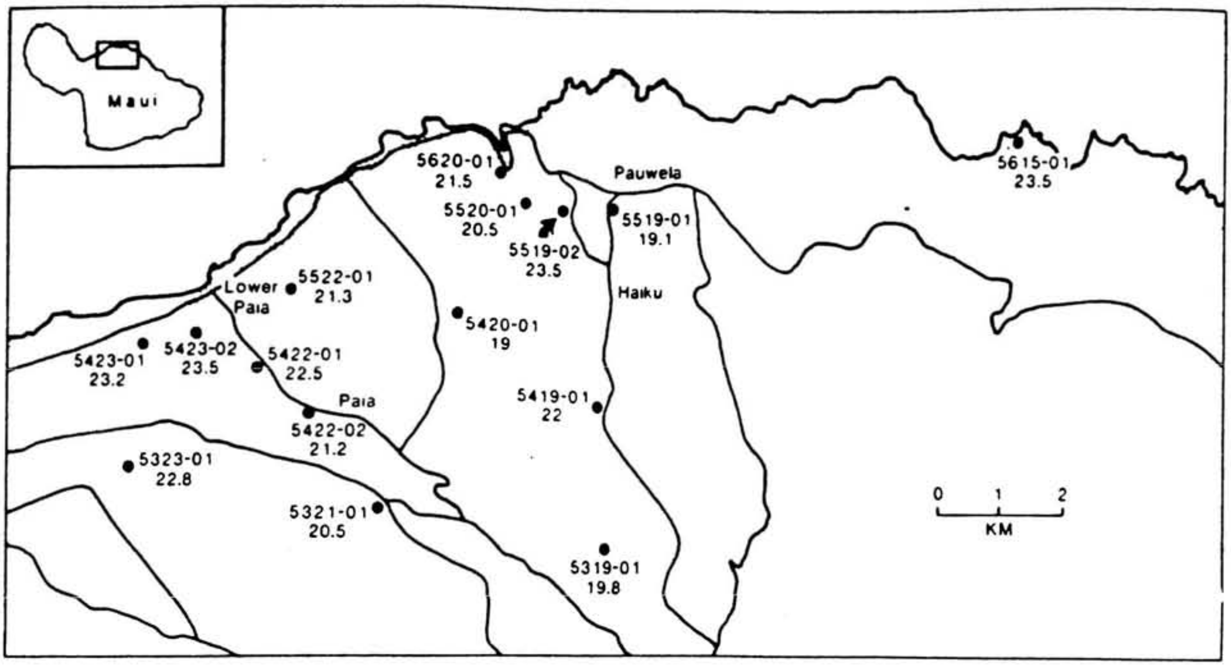


Fig. 27. Map of groundwater well locations on the Haleakala northwest rift zone (Maui is.). The upper number is the USGS well code number and the lower number is the temperature in degrees Celsius measured at each well.

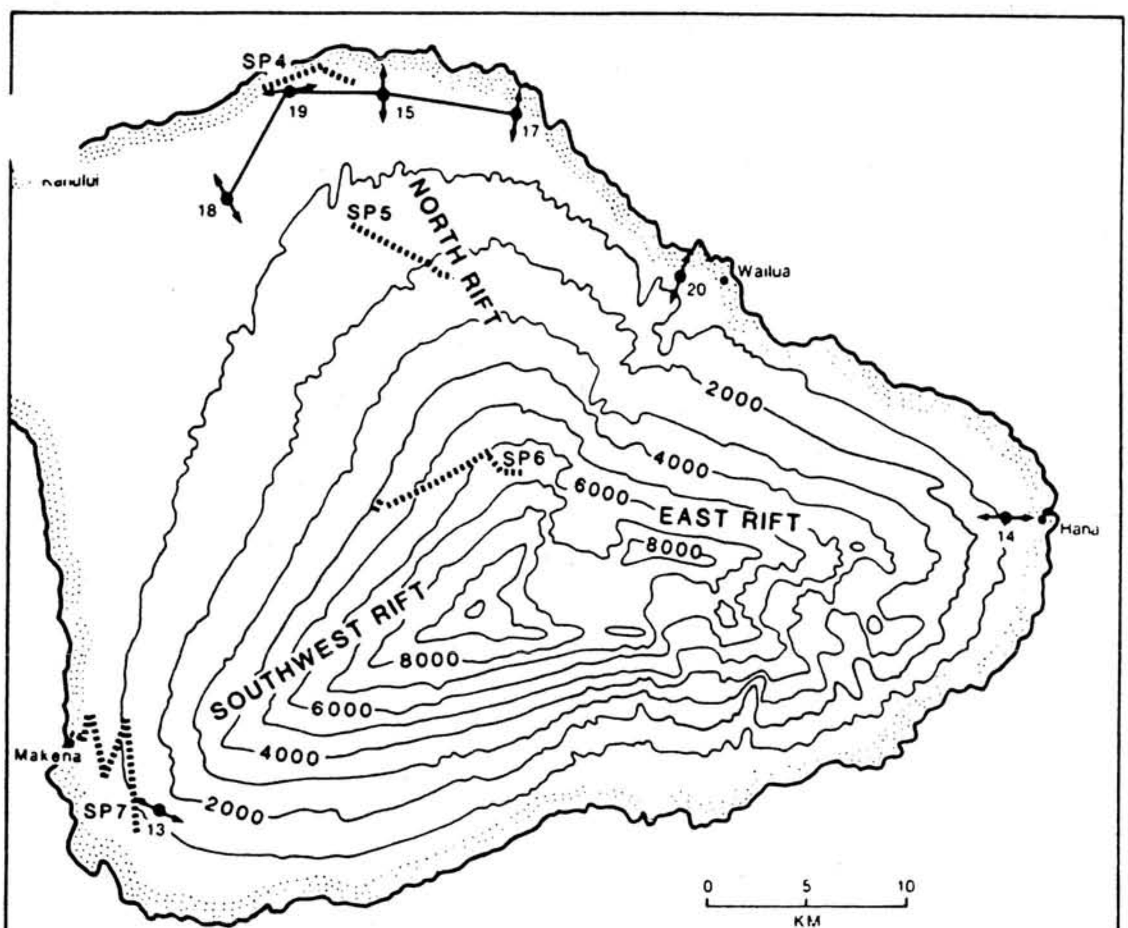


Fig. 28. Map of Haleakala volcano (Maui is.) showing the locations of Schlumberger soundings and self-potential traverses. Solid lines correspond to Schlumberger soundings and dashed lines to self-potential traverses. (From Mattice, 1981.)

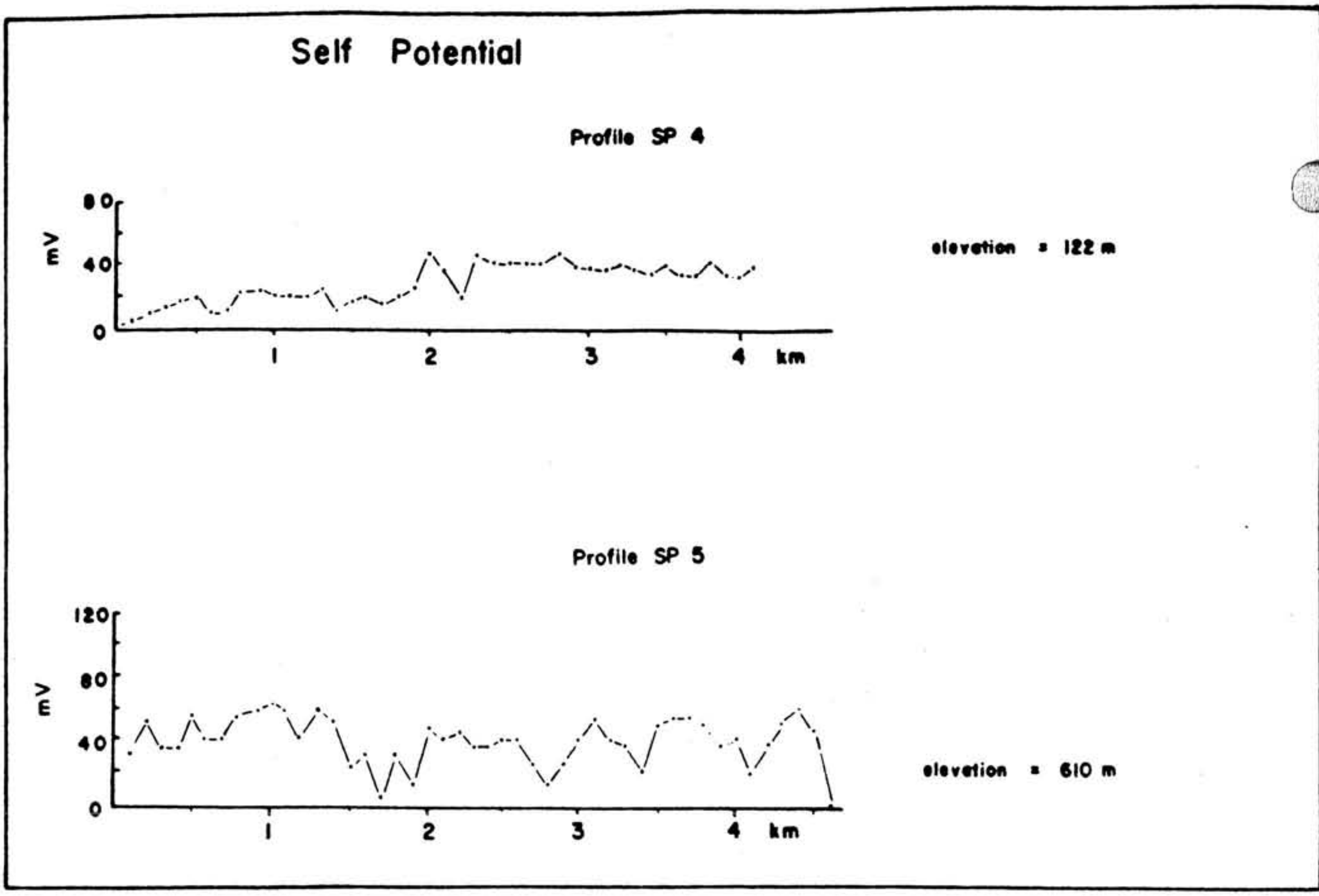


Fig. 29. Results of self-potential traverses 4 and 5 performed on the northwest rift of Haleakala volcano (Maui is.). (From Mattice and Kauahikaua, 1981.)

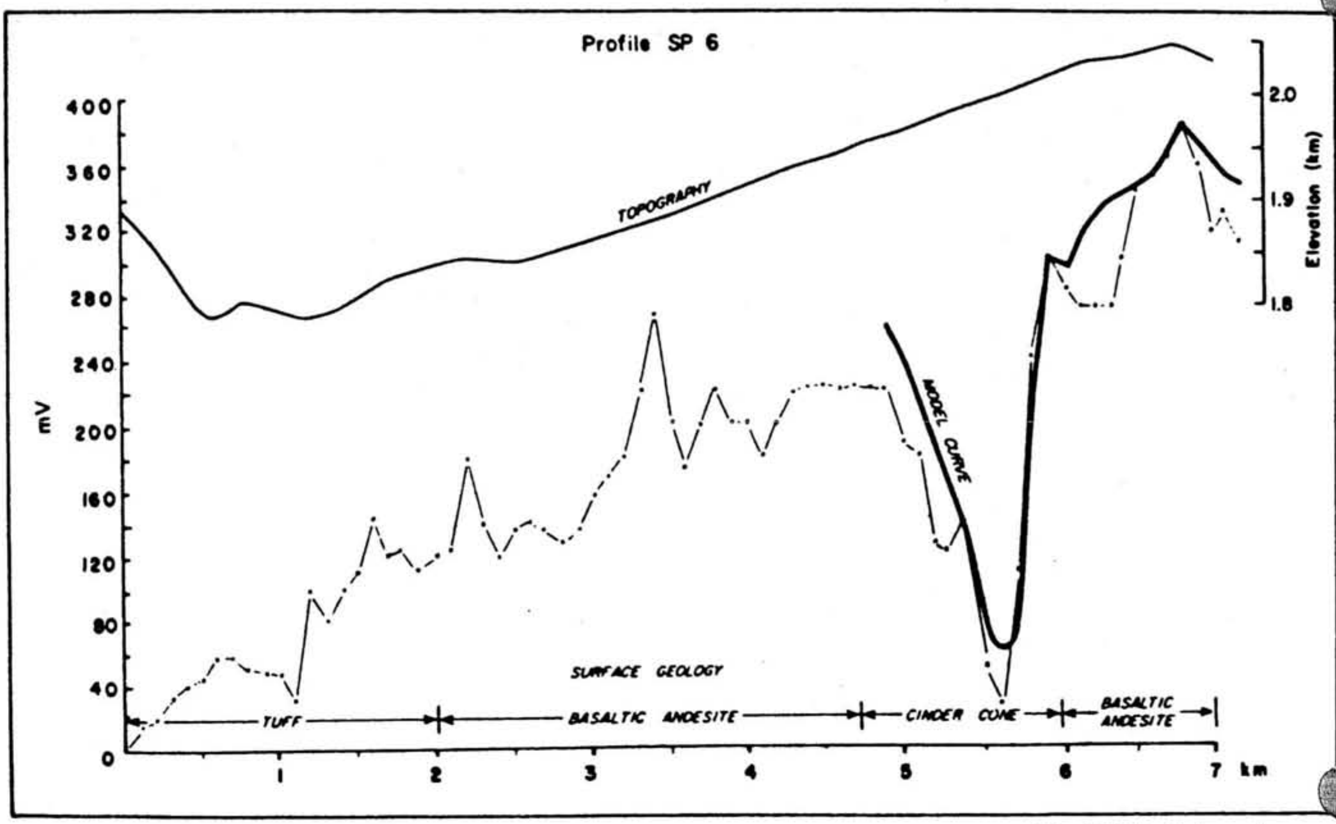


Fig. 30. Results of self-potential traverse number 6 performed on the upper northwest rift of Haleakala volcano (Maui is.). (From Mattice and Kauahikaua, 1981.)

of eruptive activity. Recent geologic mapping (Crandell, 1983) has identified several flows on this rift that are less than 10,000 years of age; a few vents are estimated to be less than 1000 years of age (J. M. Sinton, pers. commun. 1983).

Geophysical and geochemical surveys along this rift were limited by difficult field conditions and access limitations. The geophysical program consisted of one Schlumberger sounding, one self-potential profile and one controlled-source electromagnetic sounding. The geochemical data collected included a reconnaissance soil mercury and radon emanometry survey and a limited groundwater sampling program.

Geophysical surveys. The Schlumberger resistivity sounding was performed at an elevation of 546 m on the southwest rift near the site of the 1790 eruption vents (Fig. 28). Extremely high surface resistivities (greater than 20,000 ohm·m) were encountered to a depth of approximately 10 m; this section was underlain by a 255 m thick layer of somewhat lower resistivity (approximately 4000 ohm·m) and a basement with a resistivity of approximately 860 ohm·m. The upper layers correspond to a section of dry, unweathered (probably Hana Volcanic Series) basalt and a section of dry, weathered (probably Honomanu Volcanic Series) basalt, respectively. The basement at a depth of approximately 200 m is believed to correspond to a zone of freshwater-saturated basalt (Mattice, 1981).

The high resistivities encountered and the inferred elevation of the top of this layer would suggest that it more probably represents a wet but unsaturated basalt layer. If this latter interpretation is accurate, the results of this survey yield little information regarding the thermal conditions in the rift zone.

The self-potential traverse across the lower southwest rift was plagued by large potential variations arising from the high contact resistance between the sensing electrode and the dry surface rocks in the area. Although the data indicated that a weak positive self-potential anomaly was associated with the trace of the rift zone, the low signal-to-noise ratio obtained did not allow any interpretation to be made from this traverse (Mattice and Kauahikaua, 1981).

Controlled-source electromagnetic soundings were found to be substantially more successful in the southwest rift than either the Schlumberger or the self-potential studies. This was largely due to the ability of time-domain methods to penetrate high-resistivity surface layers and thus to define lower-resistivity sections at depth. The results of this sounding study, which was conducted at elevations ranging from 75 to 497 m a.s.l., generally indicated moderate- to low-resistivity (6 – 7 ohm·m) sections to depths of 1 km on the lower rift zone and higher resistivities (12 – 16 ohm·m) beneath the upper rift zone (B. R. Lienert, pers. commun., 1984). These results were interpreted to indicate that temperatures in the range of 60°C and possibly as high as 96°C were present at depths of approximately 1 km near the coast and that a colder freshwater lens was present farther inland.

Geochemical surveys. The reconnaissance soil mercury and radon emanometry surveys consisted of two traverses across the rift zone at elevations of approximately 20 m and 700 m. The results of these surveys identified several distinctive anomalies in both the soil mercury concentrations and in the radon emanation rates. The spatial coincidence of the observed variations (Figs 31, 32) suggests that they may be of geothermal significance; however, the limited coverage possible and the wide variations in soil types and land use in the survey area do not allow any definitive conclusions to be drawn from the presently available soil chemistry data.

Groundwater resources along the lower southwest flank of Haleakala are very limited in number and hence very little geochemical information is available for this area. Nine wells or springs were sampled for the current survey (Fig. 33). Six of these samples were either badly

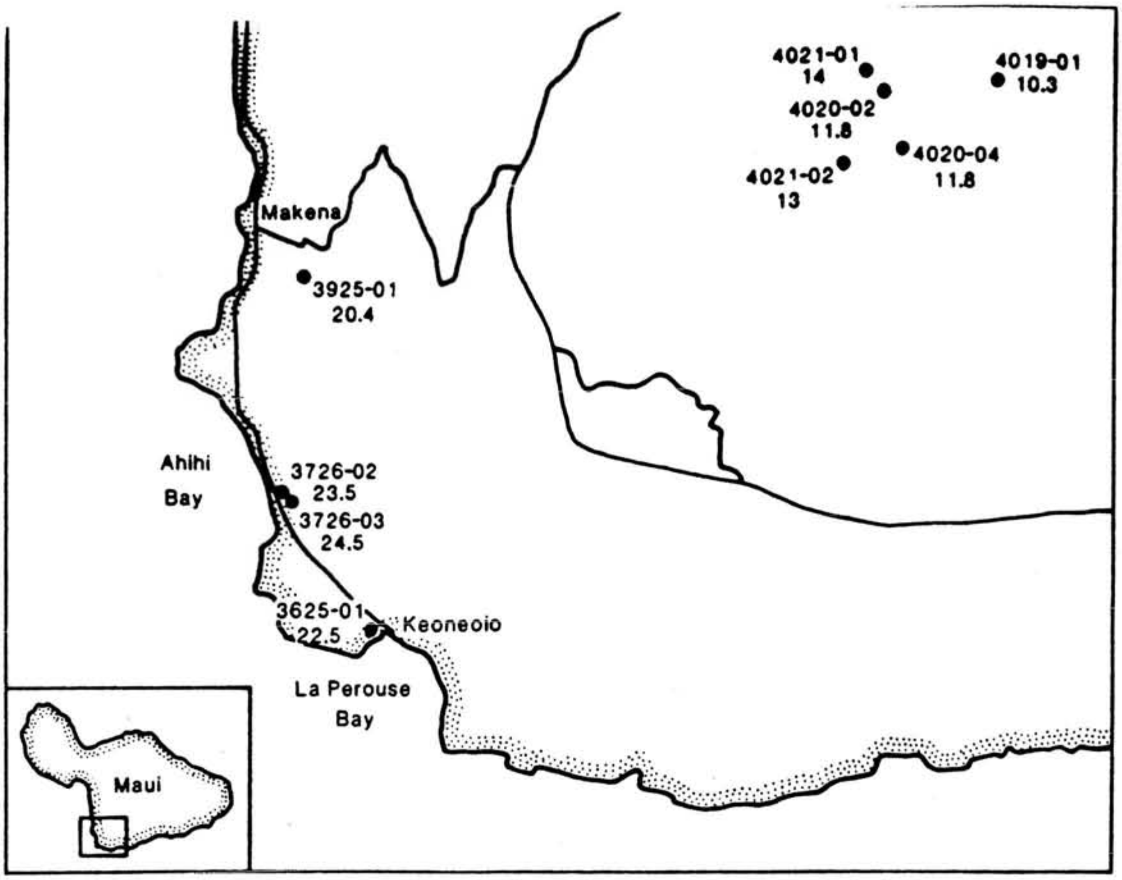


Fig. 33. Location of groundwater sources on the Haleakala lower southwest rift (Maui is.). The upper number refers to the U.S.G.S. identification number and the lower number is the temperature in degrees Celsius measured at each well.

well was also found to have an abnormally high sulfate concentration. All three wells are located in the same general area and are sampling water from the basal lens; however, the anomalous wells are reportedly not pumped on a continuous basis. Thus, although the samples acquired show distinct anomalies, the association with a potential geothermal resource cannot be confirmed at present.

Geothermal assessment. Geologic data suggest that the Haleakala east rift should have a significant geothermal potential; however, the limited nature of the data available does not allow any substantial conclusions to be drawn regarding the probability of a resource being present in this area.

HAWAII

The island of Hawaii is the youngest and largest of the chain (Fig. 34) and is made up of at least five volcanic systems (one more may be present beneath the surface flows of Mauna Loa). Kohala forms the northern tip of the island and is believed to have been formed more than 700,000 years ago (Macdonald and Abbott, 1970). Its post-erosional phase of activity—the Hawi Volcanic Series—occurred from 400,000 years before present to about 80,000 yb.p. Mauna Kea volcano is substantially younger than Kohala, the bulk of the original shield having been formed over a period from 500,000 yb.p. to approximately 15,000 yb.p. Mauna Kea is currently in its post-caldera stage of activity, producing only infrequent, scattered eruptive events; the most recent eruption is believed to have occurred 4000 years ago (Porter, 1979). Hualalai volcano is less than 400,000 years old and is currently in its late stage of activity. Its most recent eruption occurred on the northwest rift in 1801; a seismic swarm that occurred in

Table 6. Water chemistry data for Haleakala Southwest Rift, Maui island

Sample location	pH	Temp. (°C)	Na	K	Ca	Mg	Cl	SO_4	HCO_3	SiO_2	Cl/Mg	Depth	Elev.	Date
3625-01		22.5	348	41	56	178	1482	405		85	8.3	3.0	2.4	1979
3726-02		23.5	833	51	58	162	1470	452			9.1	4.6	4.0	1979
3726-03		24.5	847	46	61.2	172	1435	450		87	8.3	5.5	4.6	1979
3925-01	7.35	20.4	336	24	38	67.5	612	52	244	21.3	9.1	116.5	107.3	1978
4019-01		10.3	9.8	2.1	4.7	1.8	2.1	4.6			1.2	–	1890.2	1979
4020-02		11.8	7.7	1.9	7.5	3.6	5.6	10.1			1.6	–	1478.6	1979
4020-04		11.8	13	3.85	3.7	3.36	2.1	6.6			6.2	–	1646.3	1979
4021-01		14.0	7	1.7	3.2	3.6	3.7	9.7			1.0	–	1792.7	1979
4021-02		13.0	15	5.3	5.3	5.03	9.7	9.4			1.9	–	1451.2	1979

Concentrations are in mg/kg.
Well depths and elevations are given in meters.
See Fig. 33 for well locations.

Table 7. Water chemistry for groundwaters on the Haleakala East Rift Zone, Maui island

Sample location	pH	Temp. (°C)	Na	K	Ca	Mg	Cl	SO_4	HCO_3	SiO_2	Cl/Mg	Depth	Elev.	Date
4600-01		19.5	49.0	4.0	12.9	16.1	67.9	15.7			4.2	85.4	76.2	1979
4600-02		29.2	66.5	4.7	2.8	3.9	115.0	12.3			29.5	87.8	81.1	1979
4600-03		18.5	32.0	1.7	1.2	1.5	30.1	51.5			20.0	98.5	93.3	1979

Concentrations are in mg/kg.
Well depths and elevations are in meters.

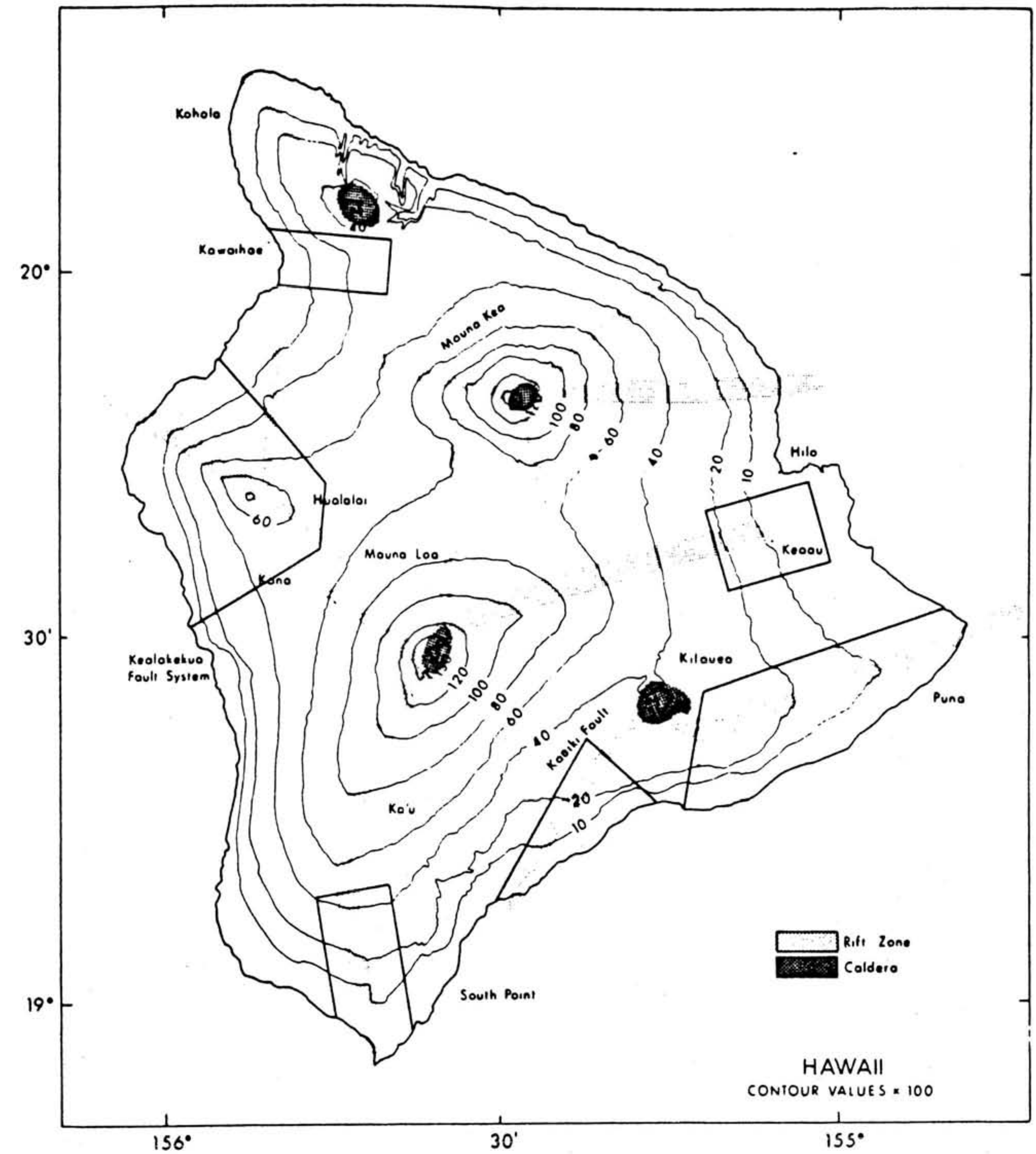


Fig. 34. Map of the island of Hawaii showing the major rift zones and calderas of each volcano. Locations of Potential Geothermal Resource Areas and field surveys are outlined. (Modified from Thomas *et al.*, 1979.)

1929 has also been inferred to have resulted from intrusive activity under its northern flank (Macdonald and Abbott, 1970). Mauna Loa is the largest volcano in the Hawaiian chain and has been formed over a period of at least 100,000 years. It is currently in its mature caldera stage of activity and last erupted in 1984. Kilauea is the youngest volcano on the island of Hawaii and has been in a state of nearly continuous eruption during the recent past.

The preliminary assessment program identified seven locations on Hawaii where available geophysical, geochemical or geological data indicated that a geothermal resource might be present (Fig. 34): (1) the northern flank of Kohala volcano, (2) Kawaihae, at the junction between the Kohala and Mauna Kea shields, (3) the Hualalai northwest rift zone, (4) the Mauna Loa lower southwest rift (South Point), (5) the Kilauea lower southwest rift (Ka'u), (6) the Kilauea East Rift Zone (Puna), and (7) the Mauna Loa lower east rift. Six of these areas were designated as Potential Geothermal Resource Areas (PGRAs), whereas one, the Kilauea East Rift Zone, was considered to be a Known Geothermal Resource Area (KGRA) due to the discovery of a productive geothermal well, HGP-A, on the lower rift. The field survey program conducted studies in all of the identified resource areas on Hawaii except the Kohala north flank. This location was considered to have the least geothermal potential and the most difficult access of all of the areas on the island; thus, field surveys were not considered to be warranted here during the current program.

In addition to the field surveys conducted under the Western States Cooperative Resources Assessment Program, a number of researchers from other federal agencies, most notably the U.S. Geological Survey, have undertaken several geophysical and geological studies on the island of Hawaii during the last five years. The data generated by these studies have been extremely useful in evaluating the geothermal resource potential of several areas on the island. This data will be reviewed in the following discussion of the resource data in order to provide as complete an evaluation of the geothermal potential in each location as possible.

Kawaihae

Kawaihae is located on the saddle of Mauna Kea and Kohola volcanoes. It is not within a recently active rift zone and hence does not appear to be a promising prospect for a geothermal resource. However, the PGRA was identified during the preliminary resource assessment on the basis of groundwater temperature and water chemistry anomalies.

Geophysical and geochemical studies conducted in this area during the field survey program confirmed the existence of the identified anomalies and tentatively identified a possible heat source. Aeromagnetic work performed by Godson *et al.* (1981) also tends to substantiate the existence of a resource in this area.

Geophysical surveys. The aeromagnetic data noted above refer to a low-level aeromagnetic survey that was flown over the entire island of Hawaii at an altitude of approximately 300 m. The results of the survey over Kawaihae clearly indicate an anomalously magnetized body between the town of Waimea and Kawaihae Bay to the west. The anomaly appears to be nearly coincident with the relatively recent (dated at 80,000 years of age by Malinowsky [1977]) post-erosional cinder cone Puu Loa.

In addition to the aeromagnetic data, the field survey program in Kawaihae included six Schlumberger resistivity soundings between Kawaihae and Waimea (Kauahikaua and Mattice, 1981).

The results of these sounding (Fig. 35) detected apparent resistivity differences in the surface rock depending on whether the soundings were done on Kohala or Mauna Kea lavas (Figs 36, 37), whereas uniform resistivities of 650 – 850 ohm·m were found at depths of approximately 30 m. Basement resistivities for these soundings ranged from 7.9 to 10,000 ohm·m. The former resistivity was interpreted to correspond to basalt saturated with seawater, whereas the latter, located to the west of Puu Loa, was tentatively interpreted to indicate the presence of a dense intrusive body associated with the Puu Loa cinder cone (Kauahikaua and Mattice, 1981).

Geochemical surveys. Soil mercury and radon emanometry traverses and groundwater temperature and chemistry studies were conducted under the geochemical field program for Kawaihae.

The soil geochemistry yielded quite complex patterns of mercury concentrations and radon

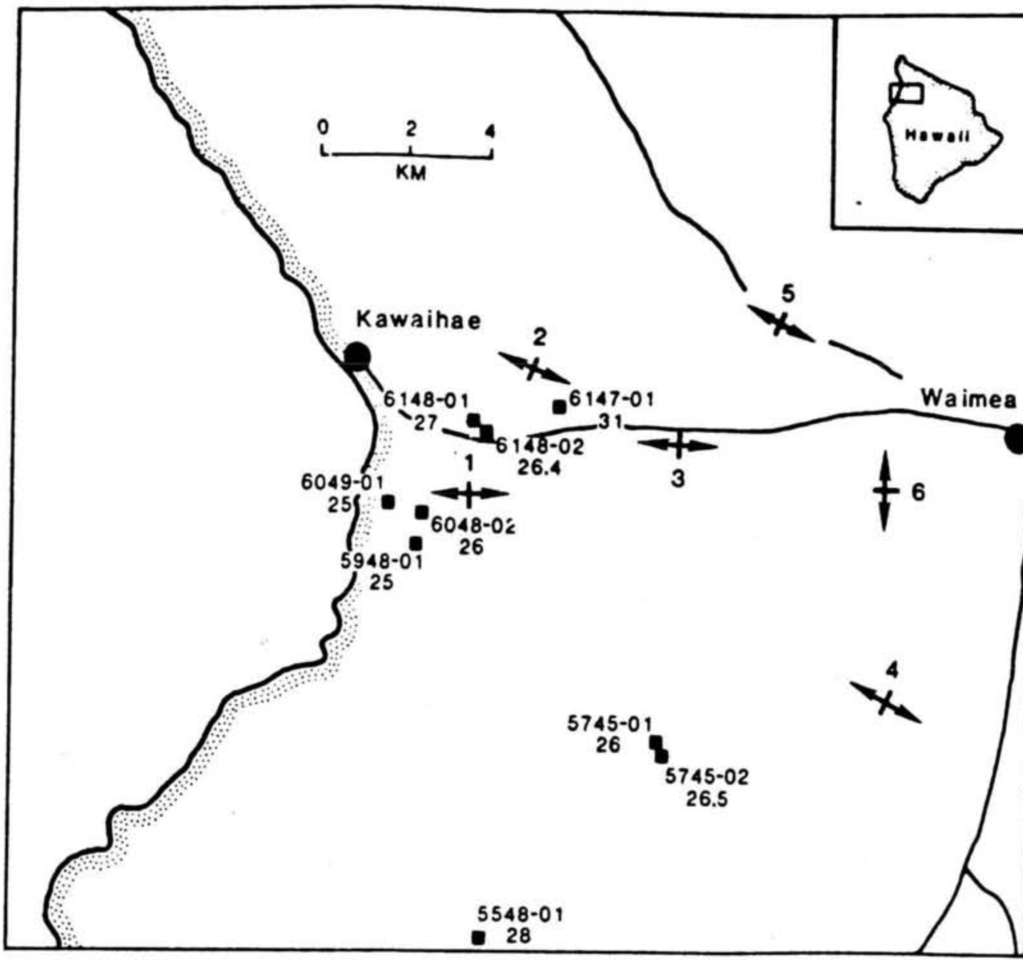


Fig. 35. Map of the Kawaihae survey area (Hawaii is.) showing the locations of vertical electrical soundings 1 – 6. Also noted are groundwater well locations (solid squares): the upper number is the well code number and the lower number is the temperature in degrees Celsius. (Modified from Kauahikaua and Mattice, 1981.)

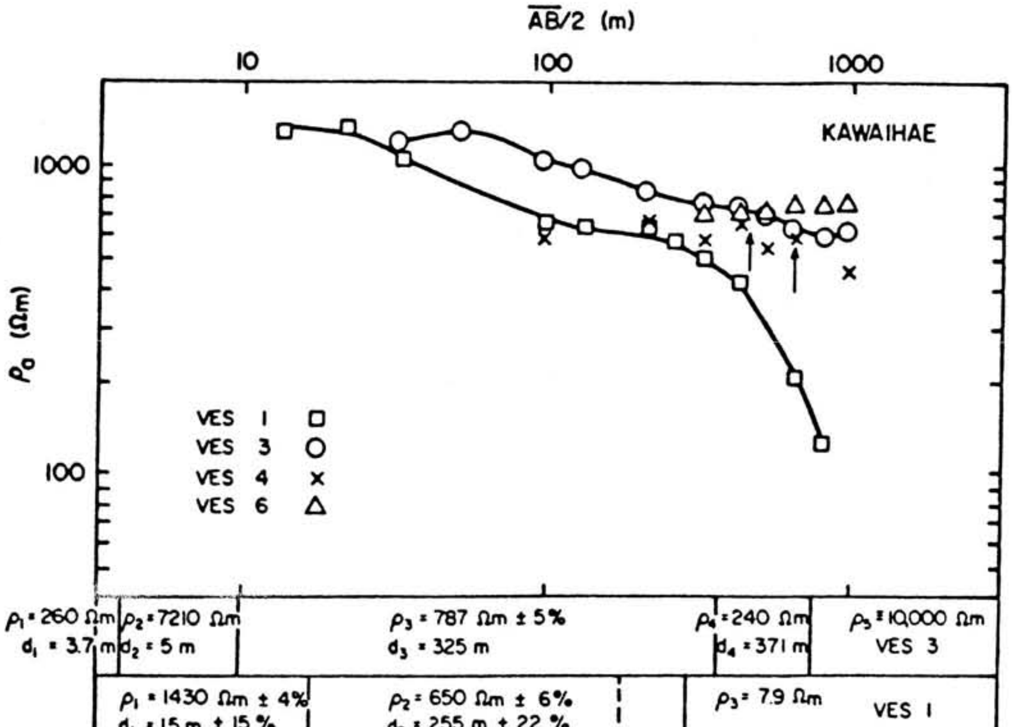


Fig. 36. Interpreted resistivity sections for resistivity soundings 1, 3, 4 and 6, Hawaii island. (From Kauahikaua and Mattice, 1981.)

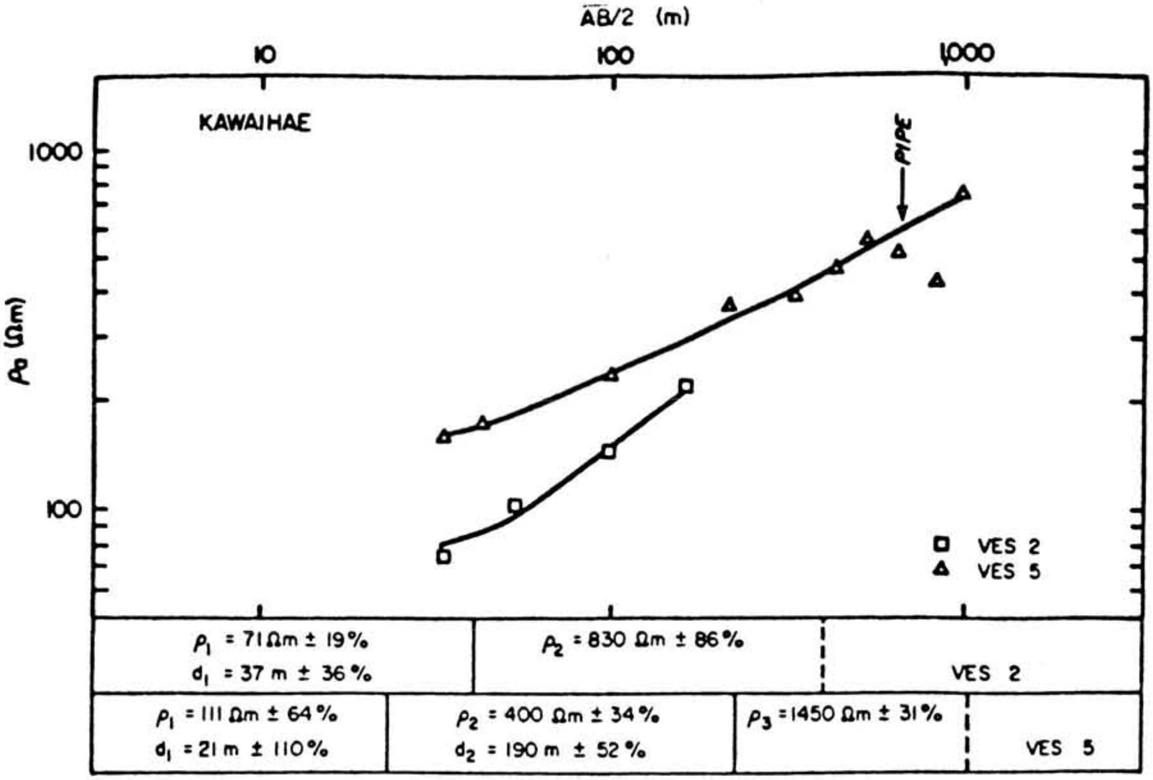


Fig. 37. Interpreted resistivity sections for resistivity soundings 2 and 5, Hawaii island. (From Kauahikaua and Mattice, 1981.)

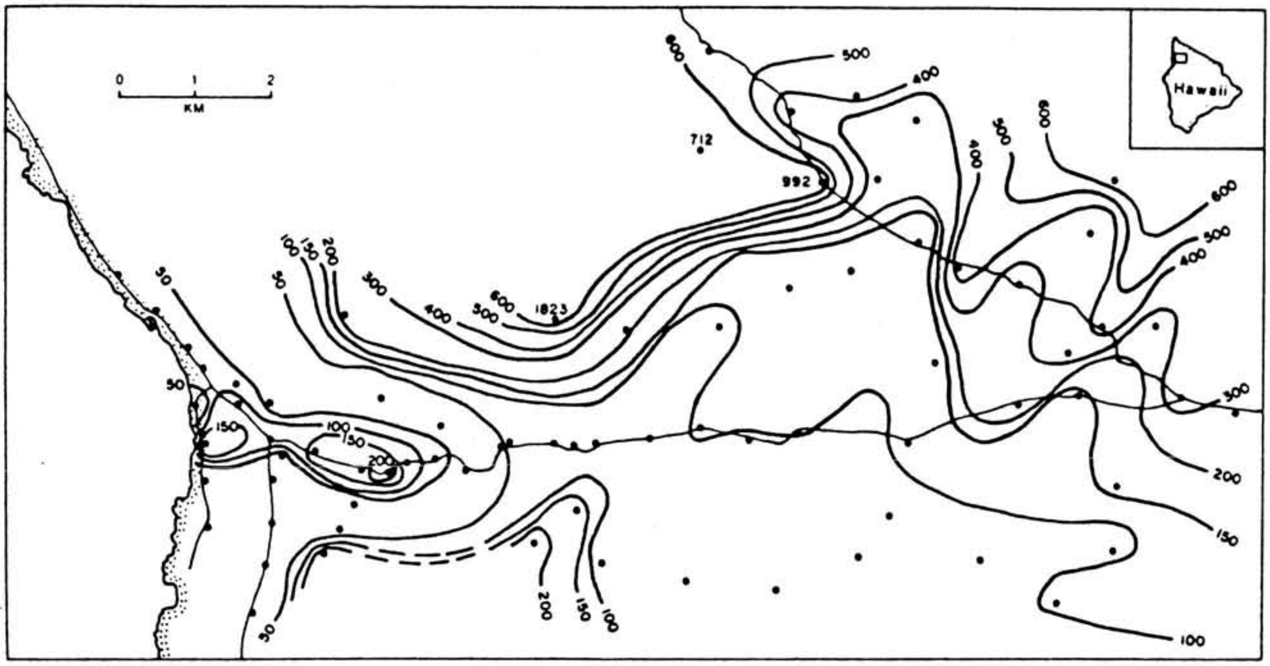


Fig. 38. Map of soil mercury concentrations found in the Kawaihae survey area (Hawaii is.). Units are in parts per billion (ppb). Dots are sample sites. (Redrawn from Cox and Cuff, 1981c.)

emanation rates within the survey area (Cox and Cuff, 1981c). Mercury concentrations (Fig. 38) showed a general minimum along the Kawaihae-Waimea roads and a broad trend of increasing mercury concentrations toward both the north and south. There is no correlation apparent between the mercury patterns and either the resistivity sounding data or the surface geology in the area. The radon emanometry data (Fig. 39) present a similarly confused pattern; the only apparent trend is a zone of moderate to high radon emanation extending northwest from Puu Loa. Thus, the interpretation possible for this data is that if a resource is present in the area, it is having a negligible impact on the soil mercury or radon emanometry patterns.

Groundwater chemical data are limited due to the small number of wells near Kawaihae; however, the data that are available strongly substantiate the presence of a thermal resource. A measured water temperature of 31°C in one well is clearly above normal ambient temperatures, and the chloride/magnesium ion ratio in the same well is elevated substantially above the normal range (Table 8). Both of these data provide strong evidence that at least a low-level thermal anomaly is present in the area. In addition, several other wells in this district show lower-order temperature and chemical variations suggestive of thermal alteration. It is believed significant that all of the anomalous groundwater sources identified are hydrologically down-gradient from Puu Loa and that other wells in the vicinity that are not down-gradient from Puu Loa do not show detectable chemical or temperature influences.

Geothermal assessment. The geophysical and geochemical data available for the Kawaihae prospect indicate that at least a limited geothermal resource is associated with the Puu Loa cinder cone on the southwest flank of Kohala volcano. The inferred eruptive mechanism for post-erosional volcanic events as well as the age of this particular vent suggest that the resource associated with Puu Loa will probably be of low- to moderate-temperature. The limited intensity and extent of the geophysical and geochemical anomalies observed tend to further substantiate this interpretation.

The probability of a low- to moderate-temperature resource existing in the Kawaihae prospect is believed to be approximately 35 – 45%; the probability of a moderate- to high-temperature resource existing here is placed at 15% or less.

Hualalai

The lavas produced by Hualalai volcano during its current phase of volcanism have been differentiated alkalic lavas typical of the waning stages of eruptive activity for the Hawaiian type of volcanism; therefore, Hualalai is considered to be in its mature post-caldera stage of activity (Macdonald and Abbott, 1970). Until recently, the frequency of eruptive activity on Hualalai was thought to be quite low—on the order of a few centuries between each outbreak. However, recent mapping on Hualalai has indicated that for nearly 1000 years prior to 1801 (the date of the most recent surface activity on Hualalai), the eruptive recurrence interval may have been as short as every 50 years (R. B. Moore, pers. commun., 1984). The 1929 seismic swarm on the north flank of Hualalai, which has been attributed to an intrusive event (Macdonald and Abbott, 1970), also suggests that Hualalai should be considered an active rather than a dormant volcano.

Hualalai was tentatively identified as a PGRA on the basis of both its recent volcanic activity as well as identified groundwater chemistry anomalies on its flanks.

The field assessment program on Hualalai consisted of vertical electrical soundings, time-domain electromagnetic soundings, soil mercury and radon emanometry surveys, and groundwater temperature and chemistry studies. Additional data used in the assessment of Hualalai include deep drilling conducted under private funding on the north flank, aeromagnetic and self-potential studies and recent geological mapping performed by personnel of the U.S. Geological Survey.

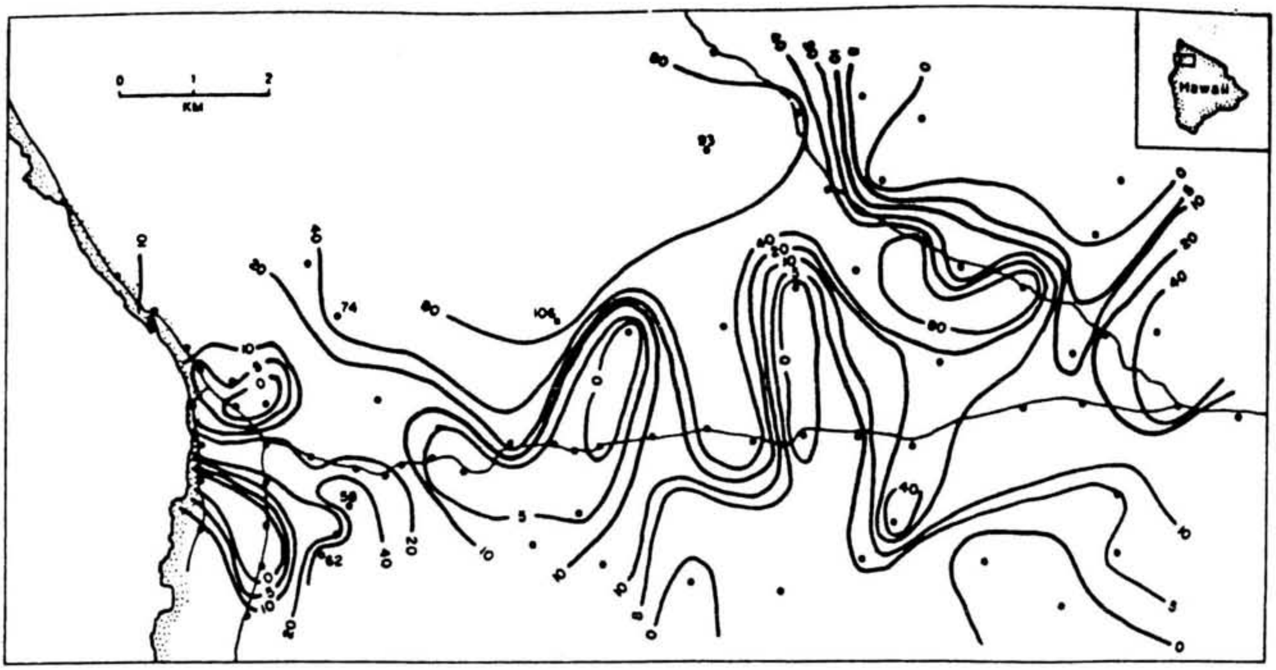


Fig. 39. Map of the ground radon emanometry results for the Kawaihae survey area (Hawaii is.). Units are in tracks per square centimeter per hour of exposure ($\times$ 100), corrected for soil background and contoured geometrically. Dots are sample sites. (Redrawn from Cox and Cuff, 1981c.)

Geophysical surveys. Aeromagnetic survey data for Hualalai (Godson *et al.*, 1981) clearly indicate an elongate northwest to southeast trending zone of extremely low total magnetic field over the summit region of Hualalai that extends into the upper northwest rift zone. It is extremely unlikely that the summit region is underlain by intrusive material old enough (greater than 700,000 years of age) to have been emplaced during a period of reversed magnetic field; therefore, the only alternative explanation possible (presuming the data are accurate) is that this region is underlain by material with very low magnetic susceptibility. This can be interpreted, then, to indicate that the summit is either underlain by a residual magma body having a temperature in excess of the Curie temperature (greater than 600°C) or that there is a zone of very heavy hydrothermal alteration beneath the Hualalai summit.

Self-potential surveys conducted over the summit and flank of Hualalai (Jackson and Sako, 1982; D. B. Jackson, pers. commun., 1983) indicate an elongate self-potential anomaly extending across the summit and down the northwest rift to Kaupulehu Crater. The positively polarized anomaly extends over an area of approximately 6 km^2 and has been interpreted to be the result of one or more buried high-temperature intrusive bodies (Jackson and Sako, 1982). Attempts to extend the self-potential profiles to lower elevations were not able to detect additional anomalies or were interfered with by buried pipelines or grounded fences.

A total of seven Schlumberger soundings were performed on Hualalai. These studies were located principally along the northwest and north rift zones (Fig. 40) (Kauahikaua and Mattice, 1981). Two soundings on the lower northwest rift (VES 1 and VES 7, Fig. 41) penetrated the high-resistivity surface layers and detected a lower-resistivity basement that was interpreted to correspond to a cold seawater-saturated basalt section overlain by dry basalt. Two soundings (VES 2 and VES 4, Fig. 41) on the middle northwest rift, at elevations of 600 – 900 m, did not penetrate a low-resistivity basement and hence were unable to yield information regarding thermal conditions on this part of the rift. Three soundings were performed on the upper rift and at the summit: one was located southwest of Kaupulehu vent (VES 6, Fig. 40) and was unable to detect even a freshwater-saturated basement to a depth of 900 m; the second

Table 8. Water chemistry data for groundwater in the Kawaihae Survey Area, Hawaii island

Sample location	pH	Temp. (°C)	Na	K	Ca	Mg	Cl	SO_4	HCO_3	SiO_2	Cl/Mg	Depth	Elev.	Date
5548-01	7.5	28	334	23.8	30	49	23	93	140	68.44	0.46	258.8	248.2	1978
5745-01	2	26	33	4.2	7.8	10.5	23	21	102	70.58	2.2	376.8	369.8	1978
5745-02	2	26.5	35	4.4	8.3	10.4	28	28	100	70.58	2.7	375.3	366.8	1978
5948-01	7.3	25	250	16.4	24	42	436	68	95	68.44	10.4	84.8	74.4	1978
6048-02	7.6	26	237	15.5	24	40	394	256	94	70.58	9.9	114.6	103.7	1978
6049-01	8.1	25	230	15	24	40	406	74	95	66.3	10.0	66.5	57.3	1978
6147-01	7.1	31	100	12.8	23	8.5	171	9	105	51.33	20.1	318.9	299.4	1978
6148-01	7.8	27	210	16.3	28	36	352	118	82	74.86	9.8	189.0	176.5	1978
6148-02	7.4	26.4	204	17.3	30	38	370	63		76.99	9.7	190.8	177.4	1978

Concentrations are presented in mg/kg.
Well depths and elevations are presented in meters.
See Fig. 35 for well locations.

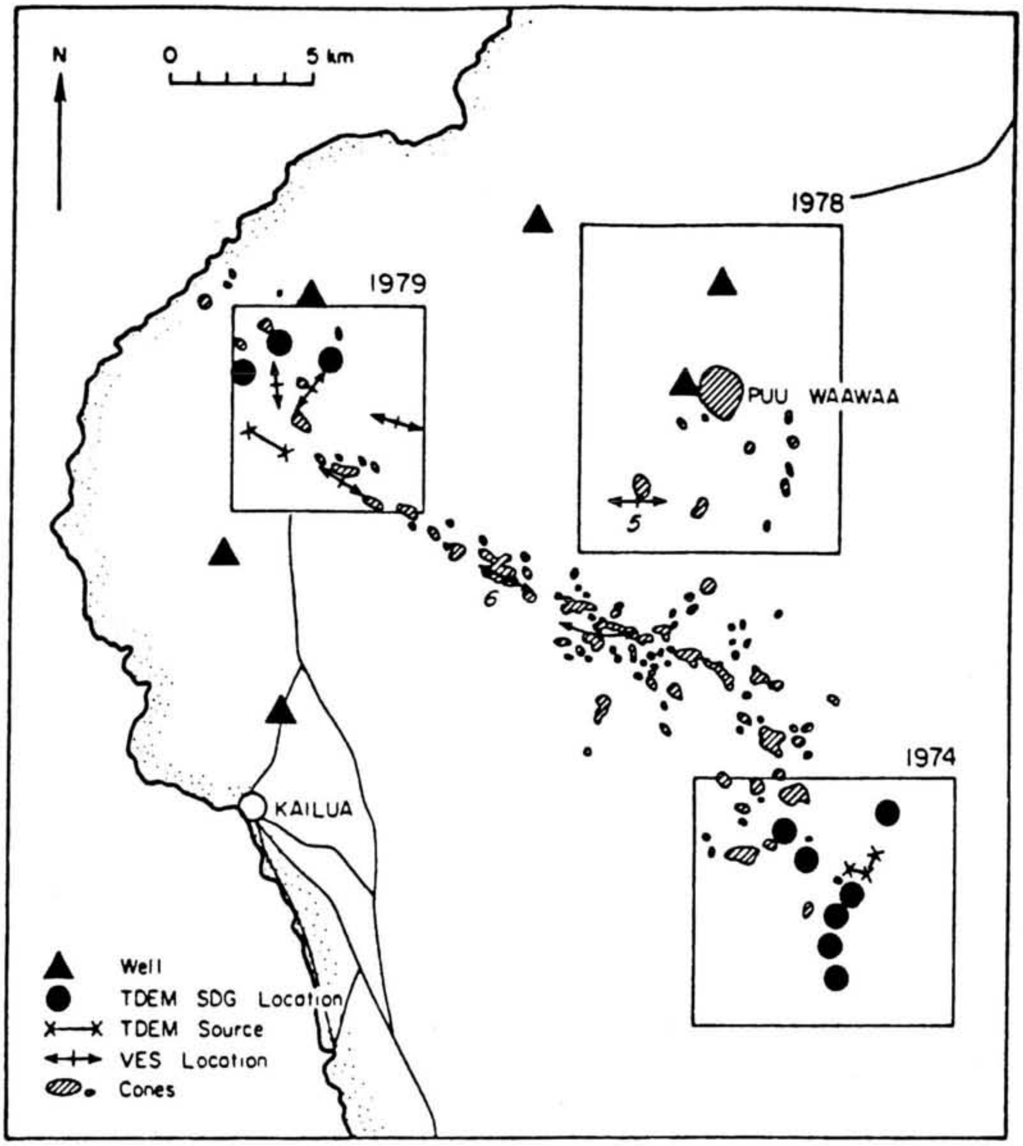


Fig. 40. Map of Hualalai volcano (Hawaii is.) showing the locations of recent surface vents and surface geophysical surveys. (From Kauahikaua and Mattice, 1981.)

sounding was located on the upper north rift (VES 5, Fig. 40) and penetrated to a freshwater aquifer having a resistivity of 800 ohm·m at a depth of 300 m; the third sounding, performed at the summit (VES 8, Fig. 40), yielded a basement resistivity too low to resolve, but was inferred to be less than 100 ohm·m at a depth of 480 m. The latter sounding has been interpreted to indicate that a perched body of (possibly) warm water is present within the summit complex (Kauahikaua and Mattice, 1981).

Three time-domain electromagnetic soundings were conducted on the middle northwest rift at elevations of 280 – 320 m (Fig. 40) (Kauahikaua and Mattice, 1981). These soundings penetrated to a greater depth than the Schlumberger soundings and two of them were able to resolve basement resistivities ranging from 9 to 12 ohm·m at depths of 1500 to 1800 m. One sounding detected a 9 ohm·m layer at 600 m depth that was underlain by a more resistive basement. These results suggest that thermal fluids may be responsible for the low-resistivity basement, whereas the high-resistivity basement could correspond to a dense intrusive body.

Geochemical surveys. The Hualalai lower northwest rift and southern flank were sampled for soil mercury concentration and radon emanation rates (Cox and Cuff, 1981d). The data generated by these surveys yielded complex patterns of mercury concentrations and radon emanation rates that generally did not show coincident anomalies (Figs 42, 43). These results were interpreted to be due to variations in soil type and to cultural effects rather than thermal anomalies (Cox and Cuff, 1981d). Surveys were not conducted in the summit area of Hualalai and hence were not able to substantiate the interpretation of the geophysical results.

Groundwater geochemical surveys were restricted to sampling and temperature measurements in coastal springs on the lower northwest rift. The coastal springs all had chemical compositions virtually identical to dilute seawater and had temperatures in the range of approximately 20°C.

Although not part of the current effort, two deep (approximately 2000 m) exploratory wells were drilled on the north flank of Hualalai near Puu Waawaa cinder cone. The geophysical data used for siting these wells were proprietary and hence unavailable for publication; however, the temperatures measured at the bottoms of the wells were reported to be below 20°C. Chemical analysis of water samples taken from these wells did not provide useful geothermal data due to contamination of the well water with drilling muds.

Geothermal assessment. The geophysical data available for Hualalai strongly suggest that a geothermal resource is present at the summit or on the upper northwest flank of Hualalai; the lower northwest and north flank are, however, not indicated to be good prospects. Geochemical data for Hualalai tends to substantiate the latter conclusion but was unable to provide information on the summit region.

The probability of a low- to moderate-temperature resource existing on the upper northwest rift or the summit complex of Hualalai is assessed at 35 – 45%; the probability for a moderate- to high-temperature resource is placed at 20 – 30%.

Mauna Loa

Mauna Loa is the second most active volcano on the island of Hawaii and has experienced numerous eruptions during historic times at the summit and along both the east and southwest rift zones (Macdonald and Abbott, 1970). The east rift zone can be traced by surface vents or lava flows down to an elevation of 200 – 300 m above sea level where its surface features have been covered by younger Kilauea lavas. The upper east rift is still considered to be active, having last erupted in 1984; however, the lower rift has produced no surface flows during recorded history. Similarly, the southwest rift zone has experienced numerous rift eruptions, but only one has been recorded below an altitude of 2500 m: the 1868 event located at an elevation of approximately 1000 m (Macdonald and Abbott, 1970).

The lower extensions of both major rift zones of Mauna Loa were identified as PGRAs during the preliminary assessment. (Although the upper rifts and caldera have been more active, current drilling technology would not be able to economically exploit a resource at elevations of more than 2500 m to 3000 m a.s.l.) The lower southwest rift, South Point, was identified on the basis of reported infrared anomalies (Abbott, 1974) as well as the geologically recent eruptive activity on the rift. The lower east rift in the Keaau area was reported to have several groundwater geochemical anomalies and hence was considered a potential resource area as well.

Mauna Loa southwest rift—South Point

Field surveys in the South Point area were limited to a series of Schlumberger soundings and a self-potential traverse across the rift zone. The absence of groundwater wells and time and funding constraints precluded any geochemical field surveys.

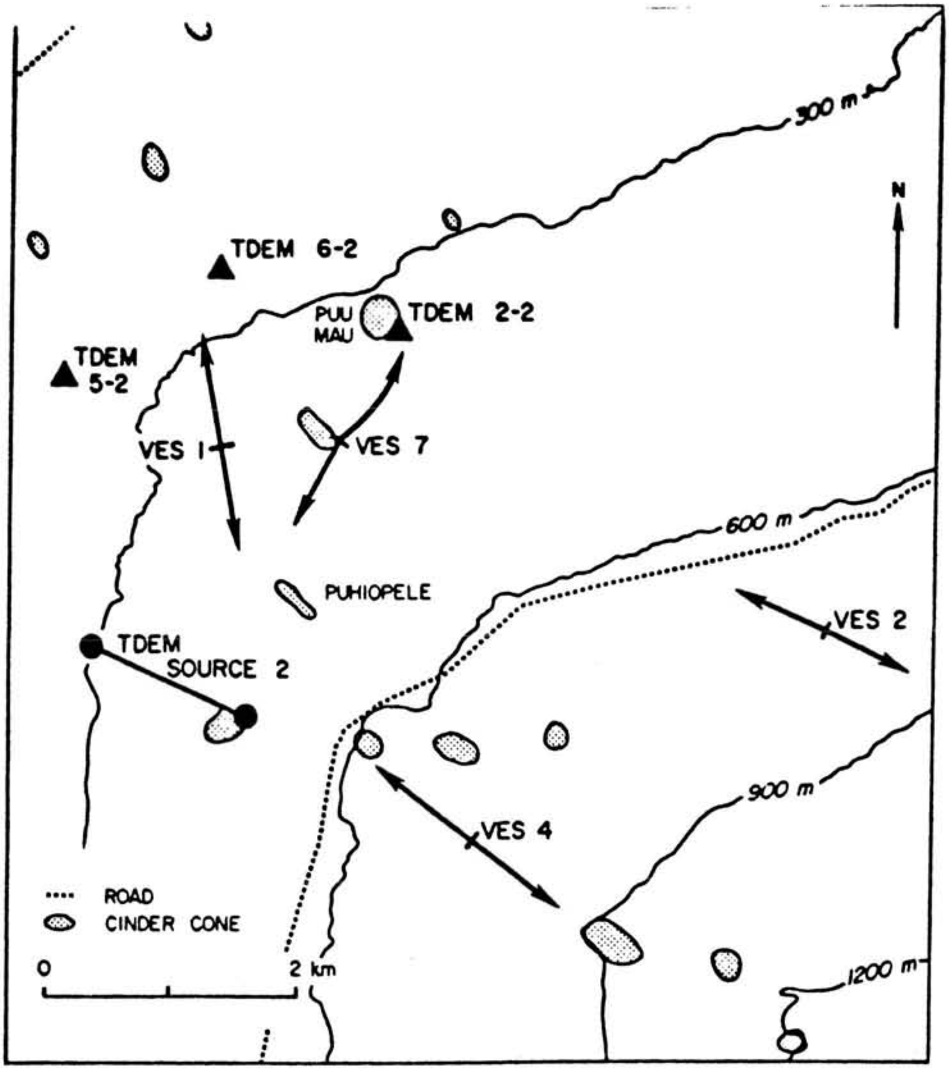


Fig. 41. Map of the upper northwest rift of Hualalai volcano (Hawaii is.) showing the location of surface geophysica surveys. (From Kauahikaua and Mattice, 1981.)

Geophysical surveys. The vertical electrical sounding surveys on the lower rift zone were confined to an area east and north of the Kahuku Fault, a major structural feature that is aligned with the strike of the lower southwest rift. Attempts were made to extend the soundings (Fig. 44) for broader coverage, but an extensive network of buried pipelines and grounded fences generated strong interferences in all but three soundings.

The three successful soundings, located within an elevation range of 300 – 1500 m a.s.l., detected basement resistivities of 600 – 5000 ohm·m (Figs 45, 46) (Kauahikaua and Mattice, 1981). The depth of penetration to the basement was estimated to be 1000 m or less. The high basement resistivities detected in the upper sounding suggest that penetration to the basal water table had not been successful because the inferred resistivities are factors of approximately 2 – 5 times those expected for freshwater-saturated basalts. The lower elevation sounding, VES 3, may have reached the basement although its resistivity of 600 ohm·m is also in the upper range of freshwater-saturated basalt values.

The higher elevation sounding, VES 4, is noteworthy for the fact that a significant resistivity discontinuity was observed on crossing the trace of a prehistoric eruptive fissure. Because of this feature, a self-potential traverse was performed along the same traverse. A pronounced negatively polarized anomaly was identified and interpreted to be the result of a downward streaming potential associated with enhanced permeability produced by the eruptive fissure

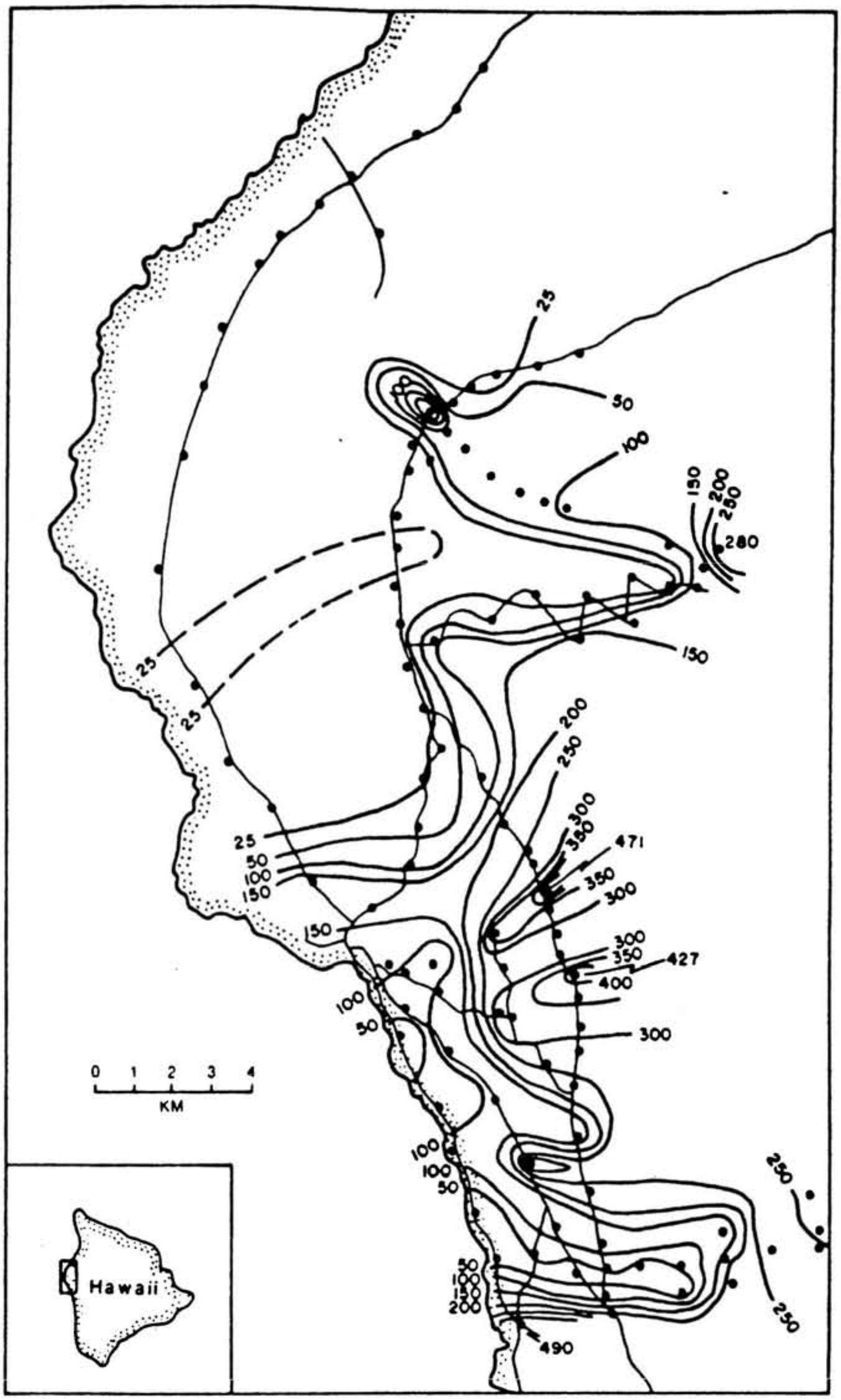


Fig. 42. Map of soil mercury concentrations found on the flanks of Hualalai volcano, Hawaii island. Light solid lines are major roads and the solid circles are sampling points. Mercury concentrations are presented in units of parts per billion (ppb). (Redrawn from Cox and Cuff, 1981d.)

(Kauahikaua and Mattice, 1981). A thermal effect was discounted as a source since most thermal features in Hawaii have been found to have positively polarized self-potential anomalies.

Geothermal assessment. The results of the preliminary geophysical surveys performed in the South Point area did not identify any significant indications of a geothermal resource associated with the southwest rift. However, the limited extent of the surveys and the interpretational difficulties encountered with the few data that were acquired warrant further studies in this area before even a tentative assessment of its geothermal potential is attempted.

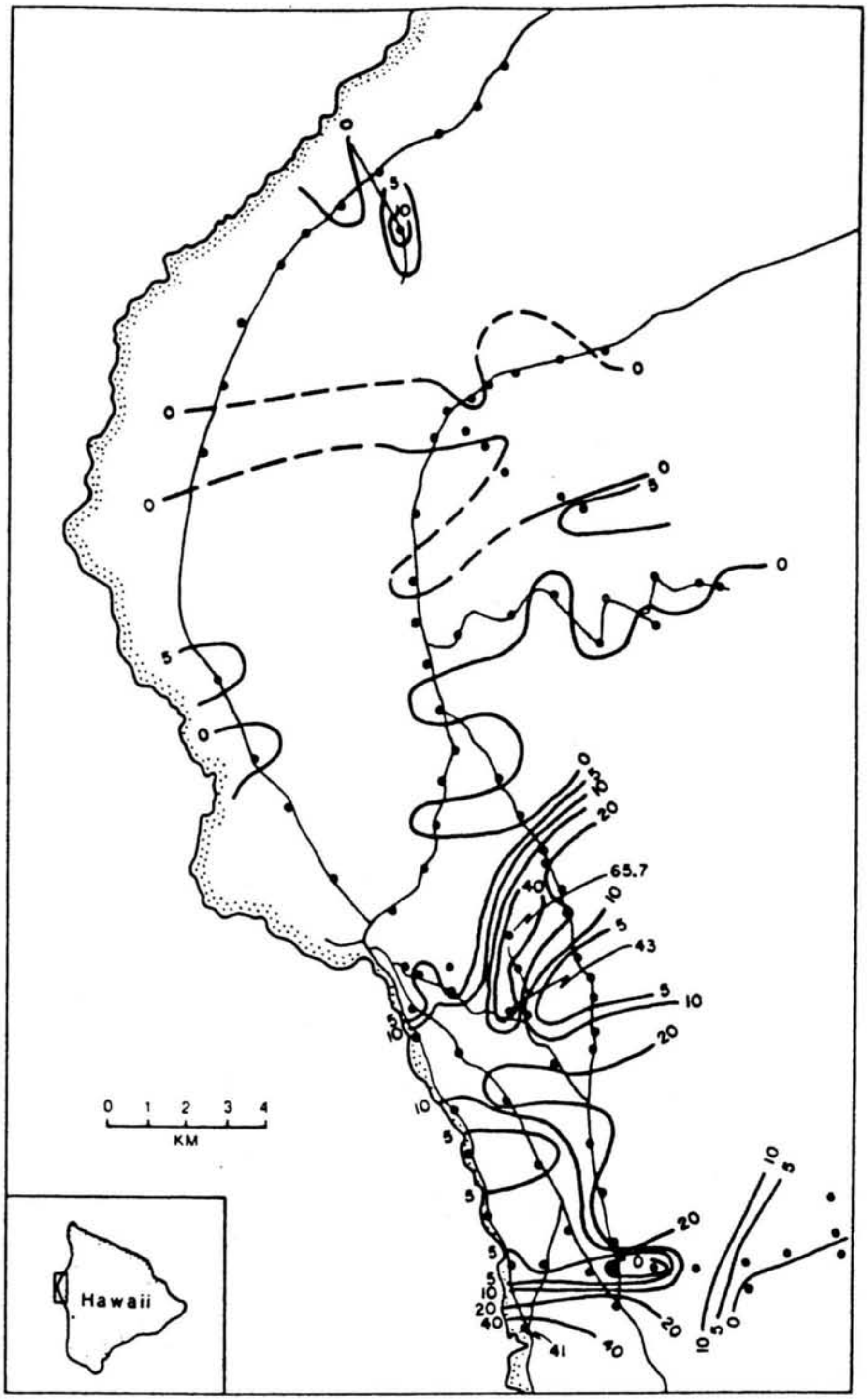
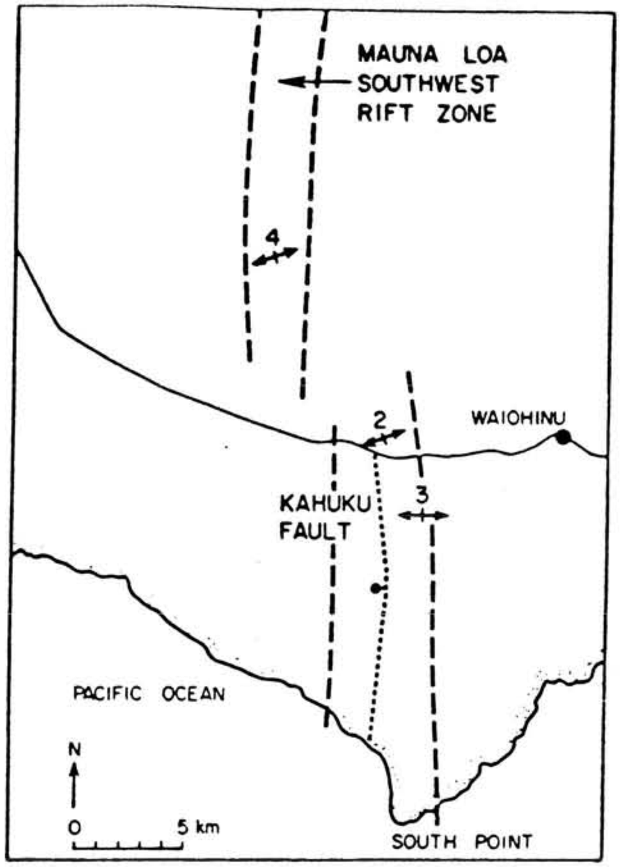


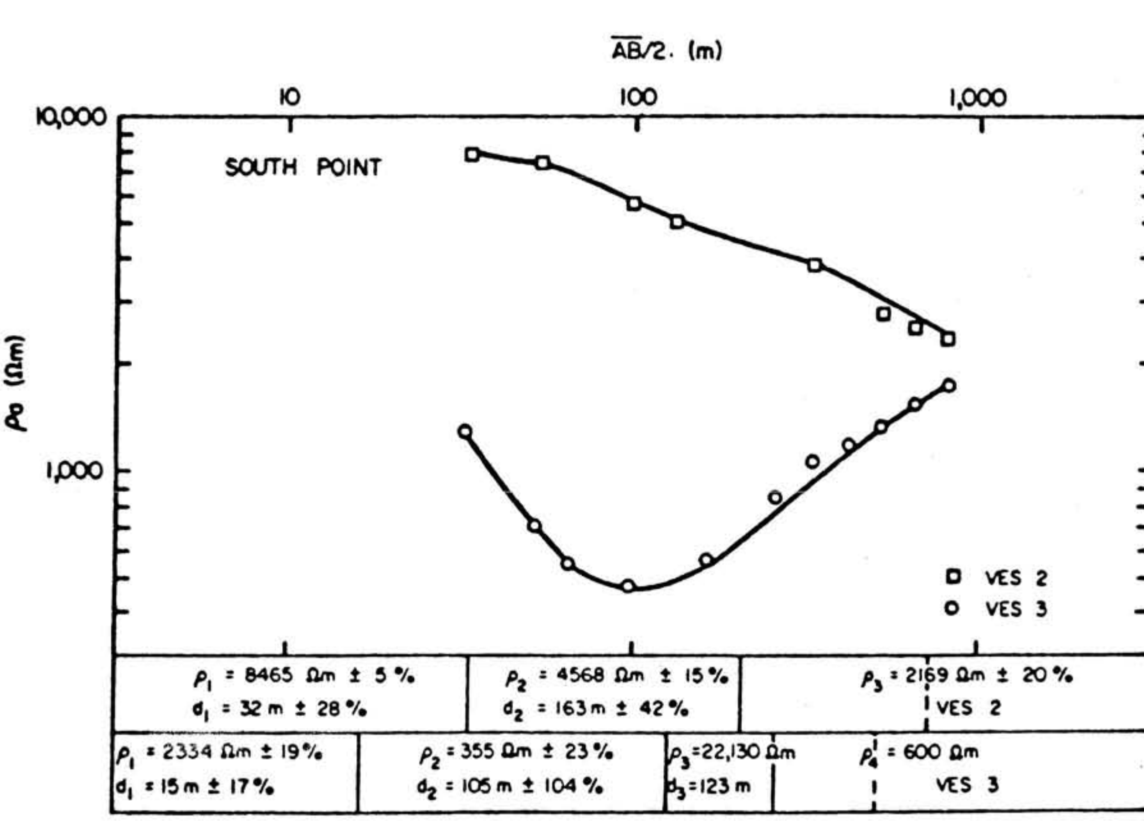
Fig. 43. Map of radon emanometry results for the flanks of Hualalai volcano (Hawaii is.). Data are presented in units of tracks per square centimeter per hour of exposure (×100), corrected for soil background, and contoured geometrically. Solid circles are radon monitoring stations and light solid lines are roadways. (Redrawn from Cox and Cuff, 1981d.)

Mauna Loa northwest rift—Keaau

Field assessment studies on the lower Mauna Loa northeast rift zone consisted of four vertical electrical soundings and four time-domain electromagnetic surveys; aeromagnetic surveys over this PGRA performed by other researchers (Godson *et al.*, 1981) have also provided valuable data for assessing the resource potential. Groundwater chemistry and temperature surveys and reconnaissance soil mercury and radon emanometry sampling ma[illegible] up the geochemical field program.



'ig. 44. Map of the Mauna Loa lower southwest rift zone showing the locations of vertical electrical soundings, Hawaii island. (From Kauahikaua and Mattice, 1981.)



}. 45. Interpreted resistivity section for vertical electrical soundings 2 and 3, Mauna Loa, Hawaii island. (From Kauahikaua and Mattice, 1981.)

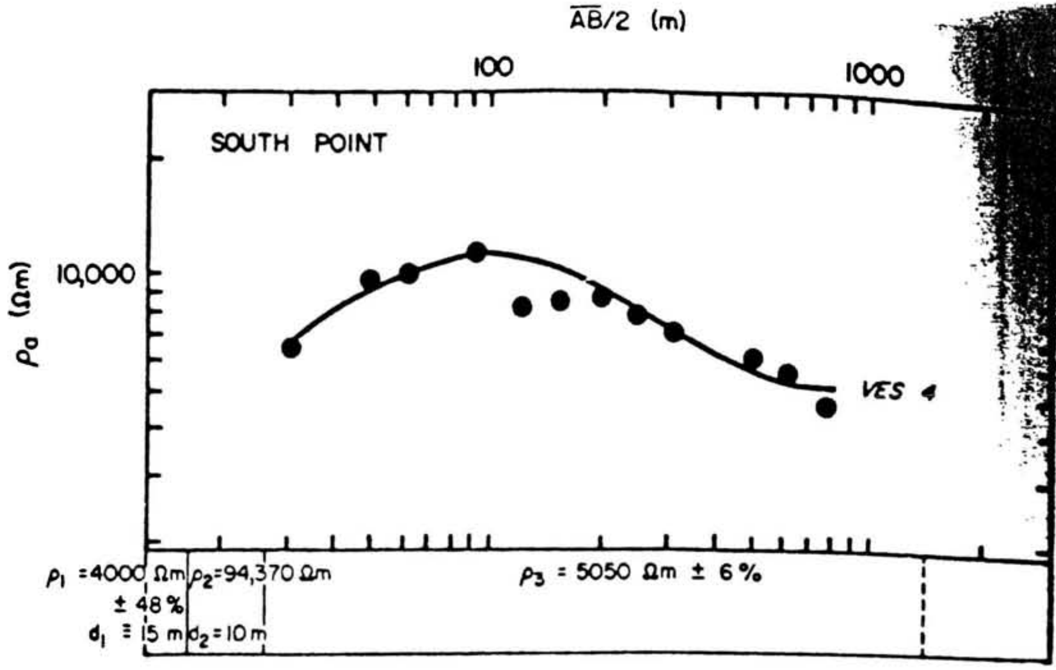


Fig. 46. Interpreted resistivity section for VES 4 conducted at South Point, Hawaii island. (From Kauahikaua and Mattice, 1981.)

Geophysical surveys. The vertical electrical sounding surveys encountered few difficulties and were able to resolve basement resistivities in all locations. The resistivity sections derived indicated a 3000 – 20,000 ohm·m surface layer underlain by a 500 – 900 ohm·m cold freshwater-saturated layer and a basement layer of less than 100 ohm·m (Kauahikaua and Mattice, 1981). The depth of penetration of these soundings was estimated to be about 800 m to 900 m b.s.l. and thus the basement resistivities probably correspond to basalts containing cold fresh to saline water. The time-domain soundings similarly indicated moderate to low basement resistivities ranging from 13 to 30 ohm·m to depths of 1 – 3 km. The electrical data all suggest that the seawater-saturated basalts in this area are at or near ambient temperatures.

Aeromagnetic data (Godson *et al.*, 1981) for the lower northeast rift of Mauna Loa tend to substantiate this conclusion as well. The lower extension of the rift zone does not exhibit any significant magnetic features that would correspond to a thermal source within the inferred trace of the rift zone.

Geochemical surveys. A reexamination of all groundwater sources in the Keaau area was undertaken in an effort to confirm the chemical and temperature anomalies that formed the primary basis on which the Keaau area was identified during the preliminary assessment survey. The data generated by this survey (Table 9) determined that all of the anomalous data present in the earlier data base were spurious and that the groundwater chemistry and temperatures in this area were entirely normal.

Soil mercury and radon emanometry sampling conducted in the Keaau prospect were similarly unable to define any anomalies that could reasonably be interpreted to be due to subsurface thermal effects.

Geothermal assessment. The geochemical and geophysical data acquired on the lower northeast rift of Mauna Loa indicate that it is extremely unlikely that a geothermal resource is present in the Keaau vicinity.

The probability of even a low-temperature resource at accessible depths existing in this area is believed to be less than 5%.

Table 9. Chemistry data for groundwater sources on the Mauna Loa Lower East Rift Zone, Hawaii island

Sample location	pH	Temp. (°C)	Na	K	Ca	Mg	Cl	SO_4	HCO_3	SiO_2	Cl/Mg	Depth	Elev.	Date
3702-01	7.0	19.7	7.2	2.1	6.9	3.3	5.08	5.5	38	38.49	1.5	61.9	67.1	1978
3802-02	7.4	19.16	6.8	1.8	4.8	2.5	3.63	10.0	86	38.49	1.5	137.2	65.5	1978
3802-03	7.8	19.44	6.3	1.8	4.8	2.5	2.49	10.0	36	27.80	1.0	115.5	65.2	1978
3802-04	7.4	19.7	6.3	1.8	4.8	2.5	3.27	10.0	38	36.36	1.3	113.1	65.2	1978
3802-05	7.4	19.7	7.1	2.1	6.1	3.2	3.86	10.0	38	38.49	1.2	114.3	65.2	1978
3900-01	7.1	18.5	41.0	3.5	8.1	7.8	66.60	10.0	44	38.49	8.5	41.8	28.0	1978
3900-02	6.8	19.5	54.0	4.0	8.8	9.7	88.40	10.0	44	38.49	9.11	44.8	29.0	1978

Concentrations are presented in mg/kg.
Well depths and elevations are presented in meters.
See Fig. 47 for well locations.

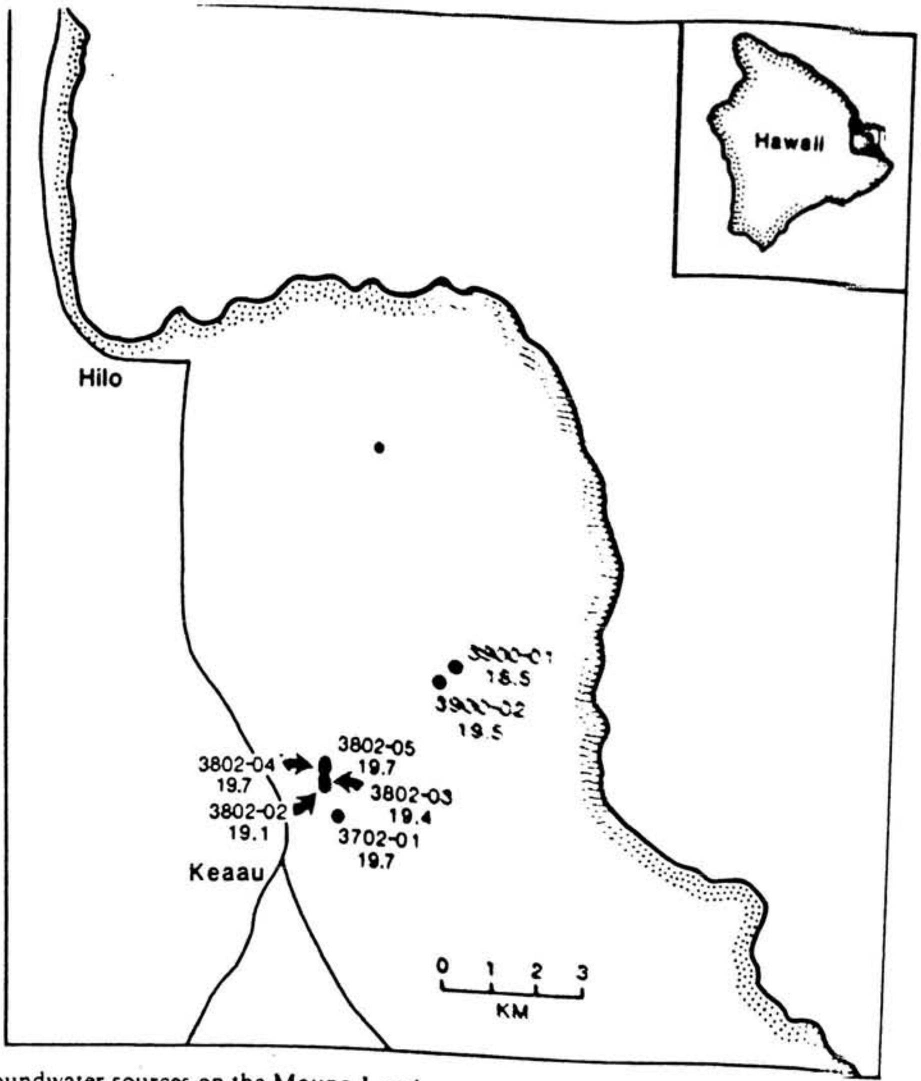


Fig. 47. Map of groundwater sources on the Mauna Loa lower east rift zone (Hawaii is.). The upper number refers to the USGS identification number and the lower number is the temperature in degrees Celsius measured at each well.

Kilauea

Kilauea is the youngest and most active volcano in Hawaii; its eruption frequency has been on the order of every one to three years during recorded history. It is presently in the midst of an extended period of activity that has been underway since January 1983 and that has produced more than 136 million m³ of lava during its first 12 months of activity (M. O. Garcia, pers. commun., 1983).

Kilauea has two principal rift zones: the East Rift Zone and the southwest rift zone. Both are considered to have geothermal potential. The East Rift Zone is considered to qualify as a Known Geothermal Resource Area due to the presence of high-temperature wells on the lower rift. The presence of warm coastal springs and steaming ground on the southwest rift indicate substantial geothermal potential on this flank as well.

Kilauea southwest rift—Ka'u:

The southwest rift zone has been the site of five eruptive episodes in recorded history; the most recent events occurred in 1971 and 1974 near the summit of Kilauea and a more recent intrusive (non-eruptive event) occurred in 1981 (N. Banks, pers. commun., 1983).

Surface manifestations of a geothermal resource on the southwest rift include a coastal spring below the middle rift area at Waiwelawela that has been reported to have a temperature of approximately 32°C (Casadevall and Hazlett, 1983) and areas of steaming ground on the upper and middle rift areas.

The majority of the southwest rift is located within the boundaries of Hawaii Volcanoes National Park and are therefore off limits to geothermal development of any kind. For this reason, only a very limited effort was made to assess the geothermal resource potential of the Kilauea southwest rift zone.

The assessment effort consisted of a reexamination of existing Schlumberger sounding (Hussong and Cox, 1967; Adams *et al.*, 1970) and time-domain electromagnetic (Klein and Kauahikaua, 1975) data for the rift area (Kauahikaua and Mattice, 1981); in addition, a preliminary interpretation of recent aeromagnetic data (Godson *et al.*, 1981) has been attempted.

The electrical resistivity data acquired on the southwest rift delineated two distinct basement resistivity structures northwest of the rift zone: a high-resistivity basement at approximately 60 m a.s.l. and located north of a prehistoric fissure, and a low-resistivity deep basement (20 m a.s.l.) to the south and east of this fissure (Figs 48, 49). These data suggest that a high-level body of cold freshwater is impounded to the north of the fissure (which is acting as a hydrologic barrier) and a deeper, warm fresh to saline aquifer lies to the southwest (Kauahikaua and Mattice, 1981). Aeromagnetic data (Godson *et al.*, 1981) for the southwest rift appears to substantiate the presence of a thermal resource; there is a marked bipolar magnetic anomaly paralleling the rift zone from the summit to the lower rift near the coast suggesting either that intense hydrothermal alteration has occurred or that subsurface temperatures exceed the Curie temperature.

Geothermal assessment. Although relatively little recent information has been gathered for the Kilauea southwest rift zone, it is clear from the available data that there is a very strong probability that a geothermal resource is associated with at least the upper and middle portions of the rift zone. The probability of a low- to moderate-temperature resource existing on the Kilauea southwest rift is estimated to be 100%. The probability of a moderate- to high-temperature resource existing in the upper rift area is placed at 70 to 80%, whereas the probability of a high-temperature resource existing in the lower rift area may be somewhat lower.

Kilauea East Rift Zone—Puna

The East Rift Zone of Kilauea volcano has experienced many episodes of eruptive and intrusive activity throughout recorded history. The results of geological mapping studies on the eastern flank of Kilauea (Holcomb, 1980) have suggested that fewer than 10% of the lava flows exposed on the surface are more than 1000 years of age. A substantial fraction of the flows blanketing the eastern slope originated on the East Rift Zone. In the recent past, eruptive outbreaks have occurred in 1955 and 1960 on the lower rift, 1955 and 1977 on the middle rift, and 1961, 1962, 1963, 1965, 1968 – 74 and 1983 – 84 on the upper rift zones.

The preliminary assessment program identified the Kilauea East Rift Zone as a KGRA on the basis of geological, geochemical and geophysical data acquired during the testing of the successful geothermal experimental well HGP-A (1960 m). During the period of time between the completion of the preliminary assessment study and the present, five privately financed geothermal wells have been drilled in the lower East Rift and several more are currently in the planning or permitting stages. All of the exploratory wells completed in the East Rift to the present date have reportedly detected high bottom-hole temperatures (greater than 200°C) although some have not encountered permeabilities high enough to produce commercial quantities of steam.

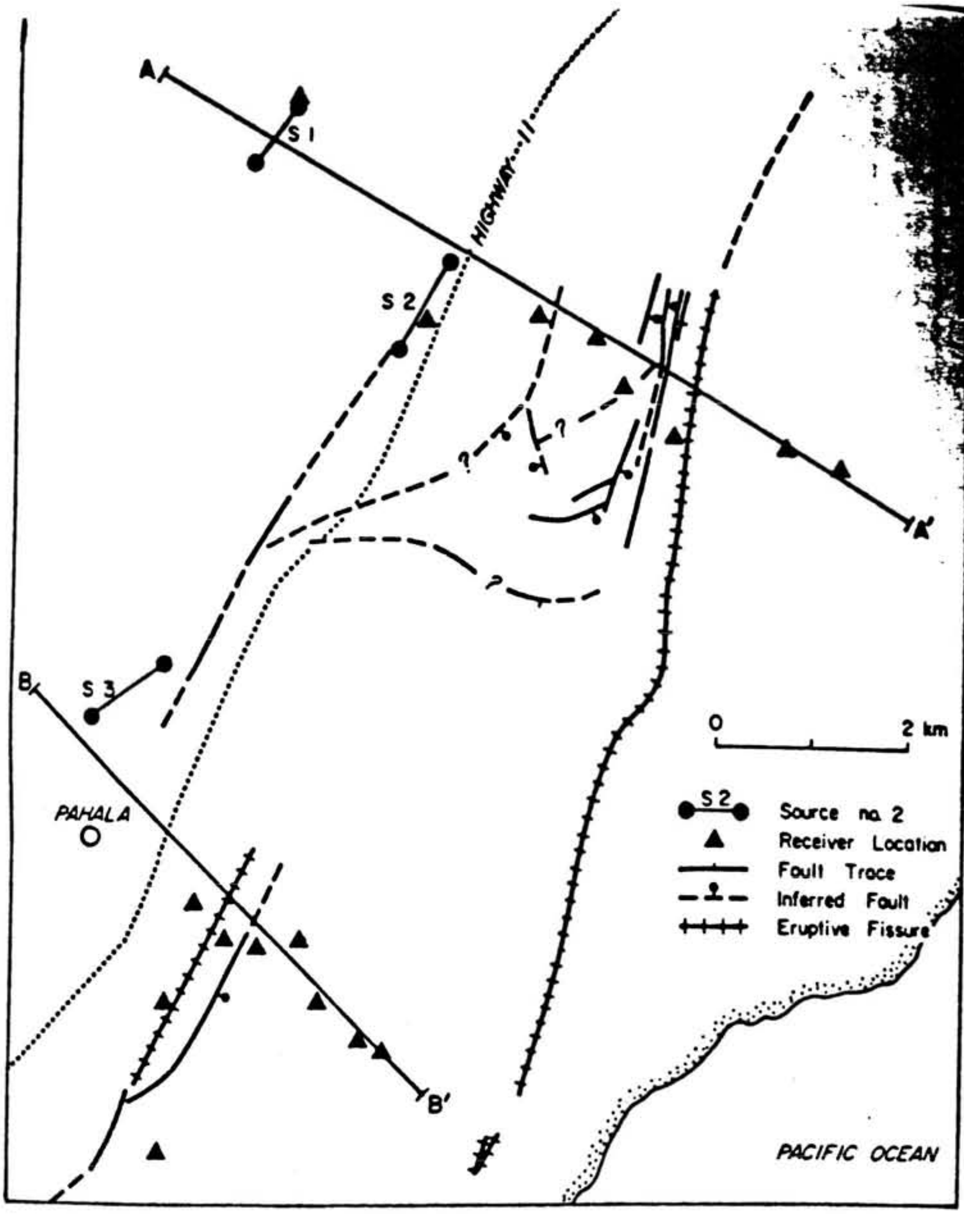


Fig. 48. Map of the Kilauea southwest rift zone (Hawaii is.) showing the locations of major surface geophysical surveys AA′ and BB′. (From Kauahikaua and Mattice, 1981.)

In spite of the fact that the East Rift Zone is considered to be a KGRA, the field assessment program performed several studies around the rift in an effort to further characterize the resource as well as provide reference data in a proven resource area in order to validate some of the survey techniques employed in other parts of the state. The data generated during the current studies, in addition to that acquired by the Hawaii Geothermal Project and by other researchers, have clearly established that a high-temperature thermal resource is present throughout the Kilauea East Rift Zone. A review of the geological, geophysical and geochemical data acquired for the East Rift will be presented as part of the statewide assessment program.

Geological studies. The geologic structure of the East Rift Zone has been studied extensively both in terms of geothermal potential and in terms of eruption mechanisms along the rift. Geologic mapping on the East Rift Zone (ERZ) conducted by Peterson (1967), J. Moore (1971), and Wright and Fiske (1971) detailed historic lava flows originating in the ERZ and developed

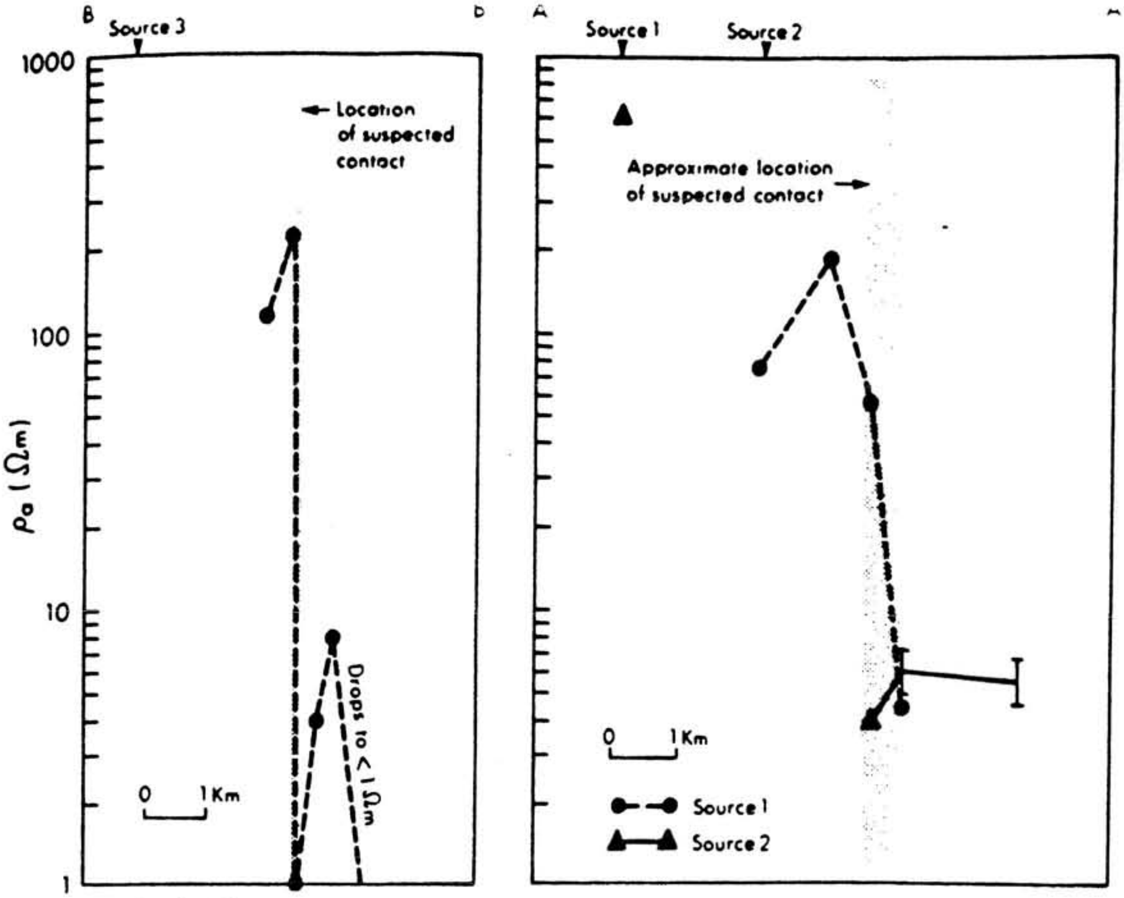


Fig. 49. Interpreted resistivity structure of the Kilauea southwest rift (Hawaii is.) on transects BB′ and AA′ (see Fig. 48). (From Kauahikaua and Mattice, 1981.)

structural models of the rift based on the locations and progressions of recorded eruptive cycles. These studies have more recently been expanded by Holcomb (1980, 1981) and R. Moore (1982, 1983) who have presented more detailed mapping of all surface flows (historic and prehistoric), fissures and faulting on the eastern flank of the Kilauea shield.

The model developed from these studies is of a rift zone composed of a series of parallel to subparallel, steeply dipping dikes which have, through time, migrated southward as the rift system has formed (Swanson *et al.*, 1976). The individual dikes have been formed from repeated intrusions of magma which have been released by the central magma chamber beneath the summit caldera into the eastern flank of the volcano. The dikes are generally thin (approximately 2 – 3 m thick) tabular bodies that individually can extend for distances of several kilometers or more along the strike of the rift zone; the vertical extent of the dikes are believed to exceed 1 km. The southward migration of the rift zone has been attributed to the presence of the immobile Mauna Loa shield to the north of Kilauea's eastern flank, whereas the southern flank is a steep submarine slope extending to the sea floor (Fiske and Jackson, 1972; Swanson *et al.*, 1976). The instability of the southern flank is evidenced by more frequent earthquake activity on the southern edge of the rift (Koyanagi *et al.*, 1981) as well as the presence of numerous fault scarps having vertical reliefs of several hundred m (Fig. 50).

Work recently completed by Holcomb (1981) suggests that the older northern portion of the rift zone may now be hidden by more recent surface flows; hence the width of the rift zone may be substantially broader than is evidenced by surface manifestations. Recent interpretations of gravity and magnetic data (Furumoto, 1978a) have also inferred a much broader—up to 30 km—rift zone than has been inferred from geologic features.

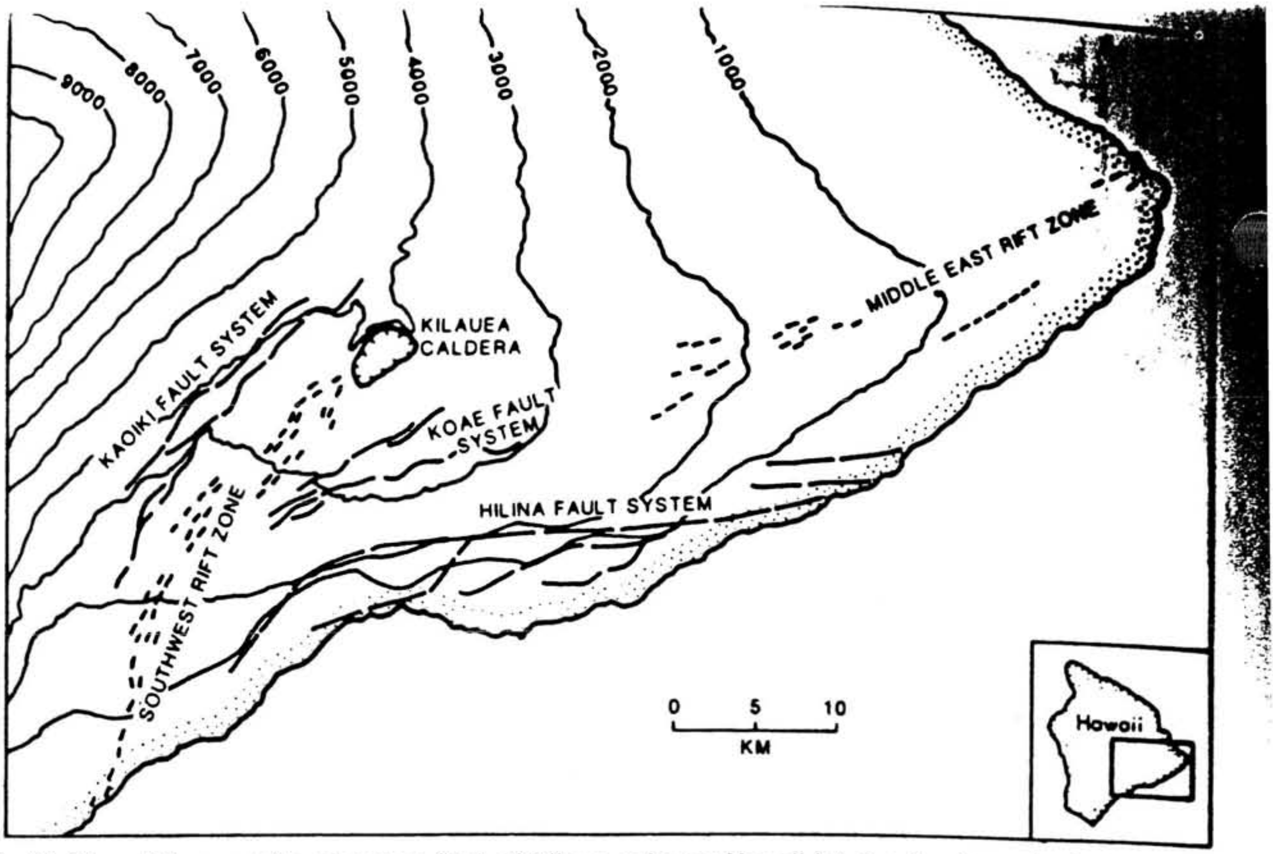


Fig. 50. Map of the summit and eastern flank of Kilauea volcano (Hawaii is.) showing the major fault systems.

Inferences regarding the thermal region within the rift zone are based on several lines of evidence. The frequency with which intrusive and eruptive events occur along the East Rift Zone would, on a purely circumstantial basis, suggest that heat recharge to the rift zone is high enough to produce subsurface temperatures well above surface ambient temperatures within the entire rift. However, studies of the petrology of the rift zone lavas (Wright and Fiske, 1971; Moore, 1982, 1983) indicate that substantial volumes of magma are stored within the rift zone for periods of time that are long enough to allow substantial magma differentiation by crystallization and mineral settling. Moore (1983) has interpreted the petrologic data from rift zone lavas to indicate that several discrete subsidiary magma chambers exist along the rift zone which are capable of storing molten magma for periods of decades to centuries and subsequently erupting substantial volumes of differentiated lava.

Geophysical surveys. Geophysical research and exploration surveys that have been conducted on the Kilauea East Rift Zone during the last 15 years include aerial infrared scanning, gravity, airborne magnetic, vertical electrical sounding, time-domain electromagnetic, ground noise, *mise-a-la-masse* and seismic reflection/refraction studies.

Analyses of the structure of the rift zone using gravity, magnetic and seismic data have yielded a somewhat different picture than that proposed on geological grounds. Seismic refraction surveys conducted by Broyles and Furumoto (1978) and Suyenaga *et al.* (1978) developed a cross-sectional model of the rift zone near the present site of HGP-A that proposed a 12 – 17 km wide dike complex lying at a depth of 2 to 3 km (Fig. 51). This model was later expanded through the examination of detailed and regional gravity data (Krivoy and Eaton, 1961) and regional aeromagnetic data (Malahoff and Woollard, 1966) to a three-dimensional map of the rift zone (Furumoto, 1978b). This model projected a dike complex (presumably at

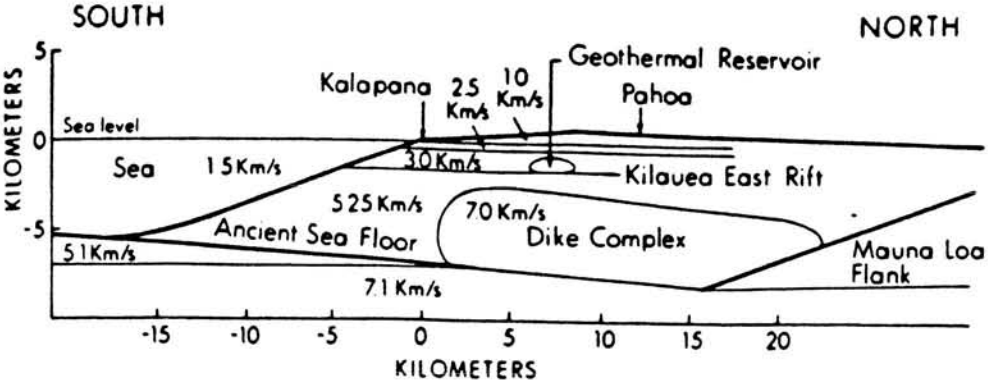


Fig. 51. Interpreted structure of the Kilauea lower East Rift Zone (Hawaii is.) on a north-south transect through the HGP-A well. This inferred structure is based on seismic refraction data. The seismic velocities of each structural feature are presented in kilometers per second (km/s). (From Furumoto, 1978a.)

high temperatures) which has a width of approximately 20 km near the summit of Kilauea that narrows to approximately 12 km at the lower quarter of the subaerial portion of the rift (Fig. 52).

Microseismic and ground noise studies were performed along the East Rift Zone in an effort to identify areas in which earthquake activity might suggest rock fracturing as a result of cold water coming into contact with heated reservoir rocks (Furumoto, 1978a). One of the microseismic surveys utilized an array of seven seismometers to monitor earthquake activity in the vicinity of the then proposed site of the HGP-A well (Fig. 53) (Suyenaga and Furumoto, 1978). The second microearthquake study utilized only two seismometers located near the junction of the Pahoa-Kalapana and Opihikao Roads (Fig. 54) (Mattice and Furumoto, 1978). The former study detected 42 events on the lower East Rift Zone; epicenter calculations showed a broad distribution within and adjacent to the rift with a majority of the events located west of HGP-A (Fig. 53). A projection of the hypocenters along a plane through HGP-A (Fig. 55) identified a broad cluster of earthquakes that were believed to be associated with the reservoir tapped by the well. The two seismometer microearthquake study similarly identified a cluster of earthquakes in the vicinity of the array (Fig. 54), but since only two seismometers were deployed, the depth and locations of these events could not be uniquely determined. The frequency of microearthquakes in this region was estimated to be on the order of 8.5 events per day suggesting that the activity in this region may correspond to a subsurface geothermal system. Seismic data accumulated by the Hawaii Volcano Observatory's seismometer array along the rift zone (Koyanagi *et al.*, 1981) indicates, however, that the entire rift is extremely active along its entire length (Fig. 56); hence the presence of microearthquake activity in the vicinity of HGP-A and the Opihikao anomaly (Mattice and Furumoto, 1978) may be more the result of placement of the arrays rather than the presence or absence of seismicity or a resource.

A study by Norris and Furumoto (1978) came to a similar conclusion regarding ground noise on the lower rift zone. Noise measurements made at frequencies ranging from 1 to 30 Hz were not able to identify a spatial correlation between ground noise levels observed and hydrothermal activity on the rift.

More recent aeromagnetic data (Godson *et al.*, 1981) generally substantiate the presence of a nearly continuous rift zone from the Kilauea summit down to sea level; the apparent width of the magnetic anomaly does not appear to match that projected by Furumoto (1978a) or Broyles *et al.* (1979); however, to date, no detailed analysis of the more recent data has been completed (R. B. Moore, pers. commun., 1984). Another feature of note in the recent aeromagnetic data is an apparent discontinuity in the magnetic field on the lower East Rift west of HGP-A. This feature is nearly coincident with an offset in the rift that has been inferred from surface features

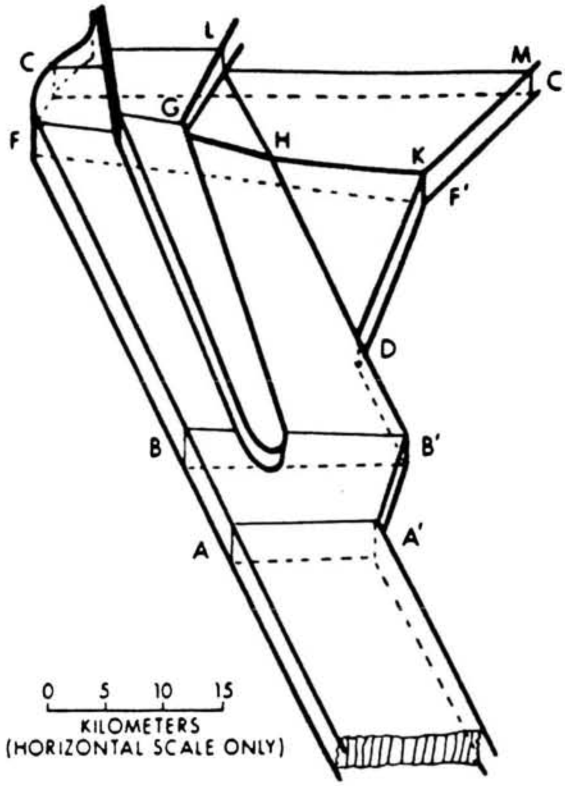


Fig. 52. Three-dimensional model of the subsurface structure of the Kilauea East Rift Zone (Hawaii is.) from the summit area to the subaerial terminus at Cape Kumukahi. The northern boundary of the rift follows the line formed by L, H, D, B′ and A′. Mauna Loa lavas are believed to lie within the volume beneath points L, M, K, D and H. The uppermost surface shown lies at a depth of approximately 2 km below the surface. (From Furumoto, 1978b.)

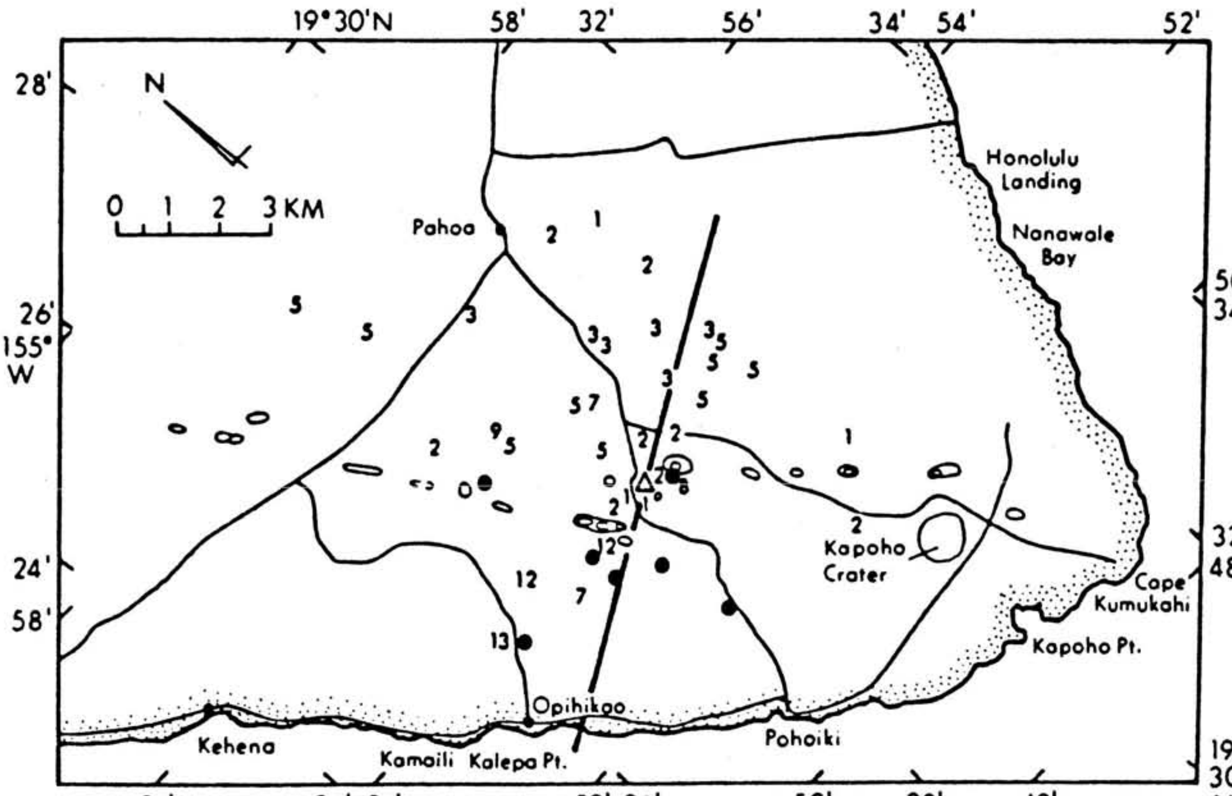


Fig. 53. Map of the Kilauea lower East Rift Zone (Hawaii is.) showing seismometer and inferred earthquake locations. The solid circles correspond to the seismometer array, the locations of the numbers correspond to epicenter locations, and the numbers denote the depth of focus of the earthquakes. The open triangle on the traverse is the location of the HGP-A well. (From Suyenaga and Furumoto, 1978.)

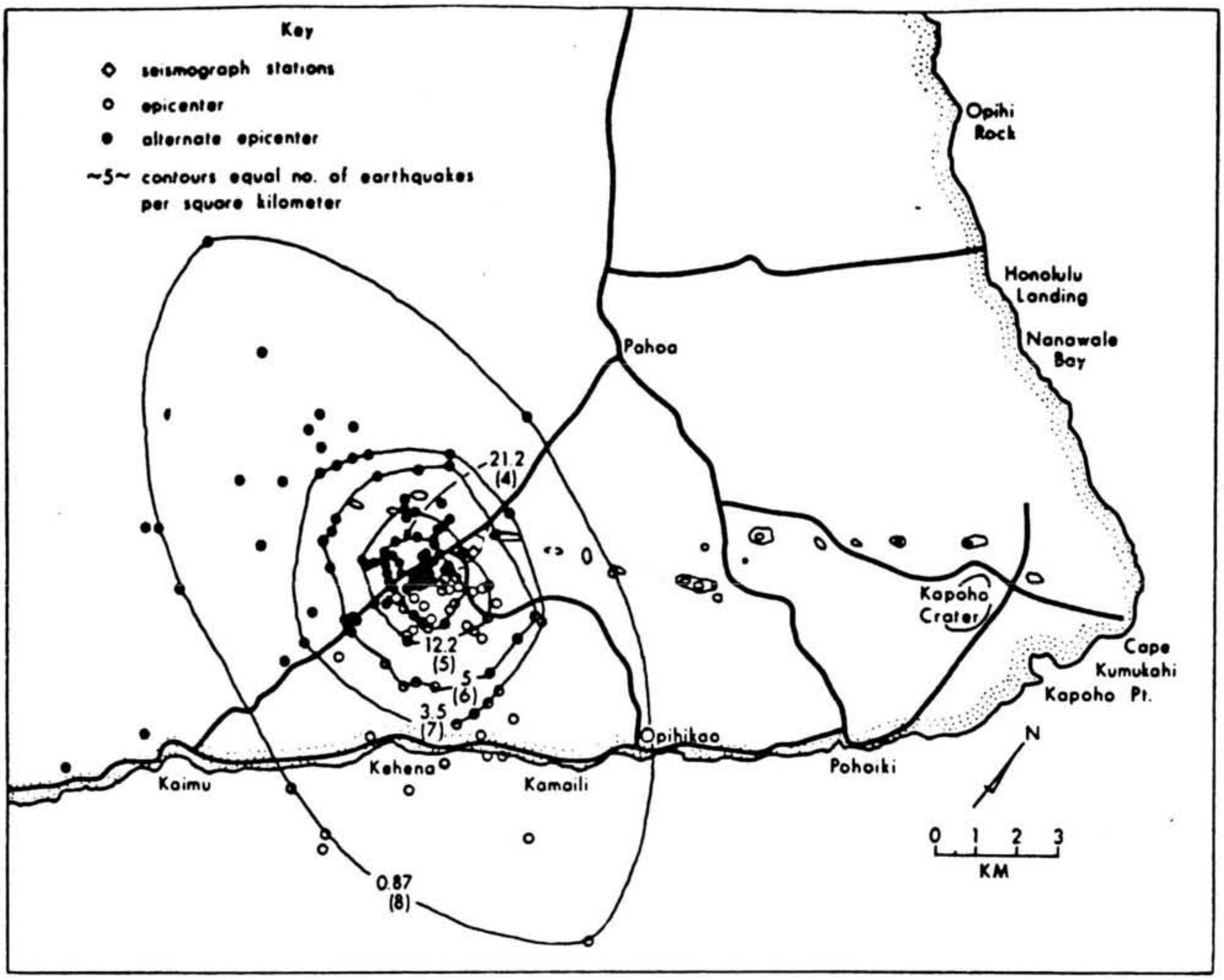


Fig. 54. Map of the Kilauea lower East Rift Zone (Hawaii is.) and possible epicenter locations for two seismometer arrays. Each contour line encloses an area of equal earthquake density (earthquakes per square kilometer). (From Mattice and Furumoto, 1978.)

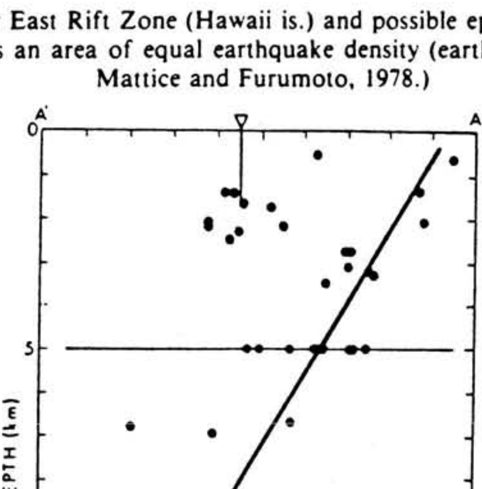


Fig. 55. Plot of earthquake foci along a transect perpendicular to the lower East Rift Zone (Hawaii is.) and through the HGP-A well (see Fig. 53 for the location of traverse AA'). The shaded area encompasses an area of clustered earthquakes inferred to be associated with the geothermal reservoir. (From Furumoto, 1978a.)

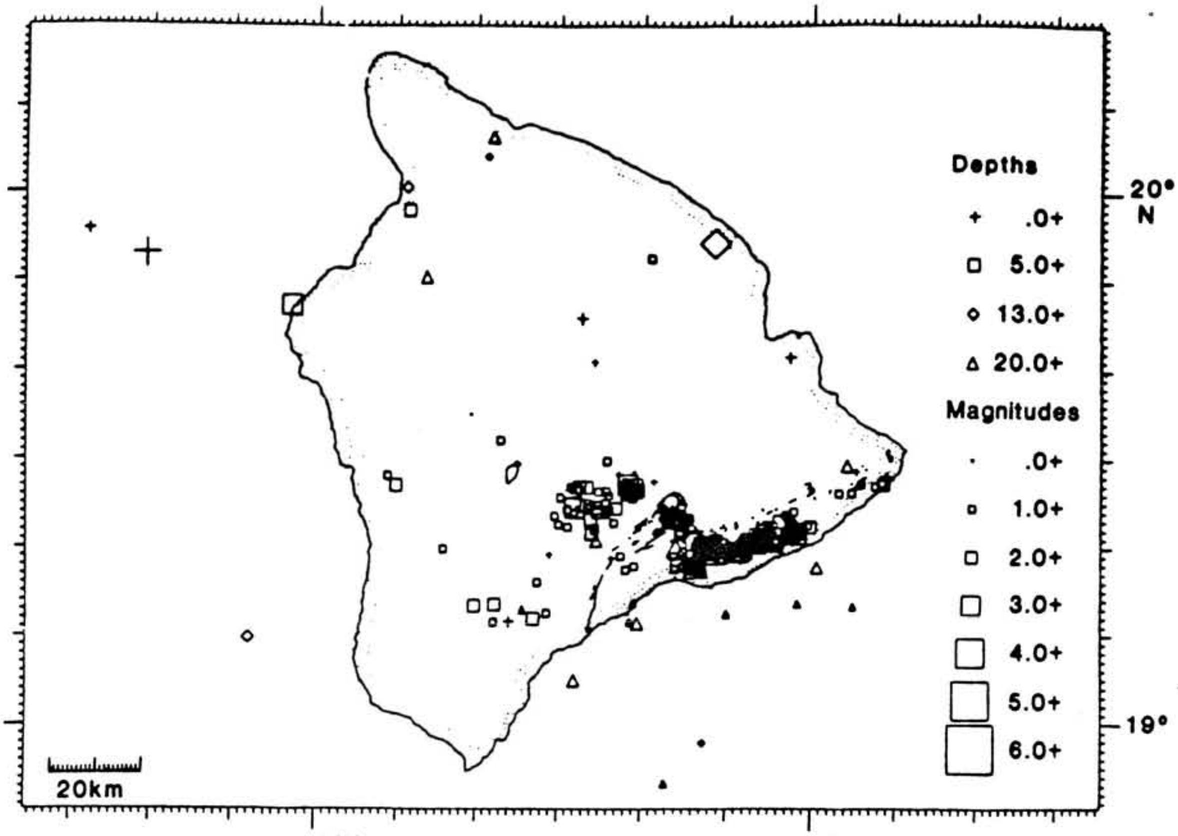


Fig. 56. Plot of epicenter locations for earthquakes on the island of Hawaii. (From Koyanagi *et al.*, 1981.)

on the rift. This coincidence would suggest that the offset is not a superficial characteristic and that it probably penetrates to substantial depths.

Electrical resistivity studies performed on the Kilauea East Rift Zone have employed a variety of techniques. Bipole mapping was conducted by Keller *et al.* (1977a) as part of the Hawaii Geothermal Project (HGP) geoscience program and was able to provide data on the regional resistivity structure of the summit and eastern flank of Kilauea. The model developed indicated several different types of resistivity sections depending on the location of the sounding on Kilauea. North of the rift zone, moderately resistive layers (200 – 800 ohm·m) corresponding to freshwater-saturated basalts were underlain by lower resistivities (20 – 30 ohm·m) that were interpreted to be a seawater-saturated basalt basement. The basement resistivities were not resolved well enough using this technique to determine whether or not the seawater-saturated layers were above ambient temperatures. Surface resistivities within the summit caldera were found to be generally higher (1000 – 2000 ohm·m) to depths of 2 – 3 km; basement resistivities beneath the caldera were generally much lower (5 – 30 ohm·m), indicating either saline fluids or, more probably, higher subsurface temperatures. The resistivity structure within and to the south of the East Rift was indicated to have surface resistivities comparable to those north of the rift, but lower basement resistivities (4 – 5 ohm·m) at considerably shallow depths (0.5 km) (Keller *et al.*, 1977b).

A series of time-domain electromagnetic (TDEM) soundings were also performed in the lower East Rift Zone as part of the HGP exploration program (Klein and Kauahikaua, 1975; Kauahikaua and Klein, 1977); this work was recently expanded to include additional TDEM and vertical electrical soundings, and the entire data set was reinterpreted (Kauahikaua, 1981b; Kauahikaua and Mattice, 1981). The resistivity model presented by Kauahikaua (1981b) suggests that moderate to high basement resistivities, corresponding to cold freshwater-saturated basalts, are present north of the rift zone and west of the intersection of highway 13 with the rift (Fig. 57). Much lower basement resistivities (2 – 10 ohm·m) are found both within the rift to the east of the HGP-A well, and south of the rift to the east of its intersection with highway 13. The lower basement resistivities are attributed to the presence of thermal fluids associated with the rift zone; the low resistivities south of the rift may, however, also be the result of the higher concentrations of low- to moderate-temperature saline groundwaters that have been found in this area (Kroopnick *et al.*, 1978).

A third type of more site-specific electrical data was gathered on the lower rift using a *mise-a-la-masse* survey. This technique employs a deeply penetrating conductive electrode, in this case the HGP-A well casing, and measures surface potentials surrounding the current source. This study found a high-resistivity structure surrounding the well that declined to lower resistivity at a distance of 1 km to the north and south (Fig. 58). This structure was interpreted to represent a dike-impounded body of fresh-water within the rift that extended to depths of approximately 1 km. The impounding features were interpreted to be high-temperature, low-resistivity dike complexes associated with recent eruptive vents to the north and south of HGP-A.

An extensive network of self-potential surveys have been performed over the summit and flanks of Kilauea as part of the HGP exploration surveys and in separate studies of the source mechanism for the potential anomalies observed (Zablocki, 1976, 1977). The geothermal exploration surveys were performed primarily on the lower East Rift Zone and identified four separate self-potential anomalies (Fig. 59) (Zablocki, 1977). The source mechanism for the anomalies observed was inferred to be the result of electrokinetic phenomena; thermal groundwater escaping from a geothermal system may be capable of generating electrical potentials by differential adsorption of negative or positive ions onto rock surfaces (potential differences of 1.5 volts over distances of 1 km have been observed over known thermal features at the Kilauea summit [Zablocki, 1976]). The self-potential anomalies observed in lower Puna are more noteworthy by the fact that they were one of the primary bases used for identifying a drilling location for the HGP-A geothermal well.

Numerous other self-potential surveys have been performed on the upper East Rift and in the summit area of Kilauea (Zablocki, 1976; D. B. Jackson, pers. commun., 1983). Distinct self-potential anomalies have been frequently found in association with fumaroles or intrusives that were known to be at high temperatures; however, the majority of these studies were performed within the boundaries of the Hawaii Volcanoes National Park and hence are of little value in identifying commercially valuable geothermal resources.

Geochemical surveys. Geochemical studies on the Kilauea East Rift Zone have included extensive soil mercury and radon emanometry networks and repeated surveys of groundwater chemistry and temperatures. Due to problems with accessibility and the absence of groundwater sources on the middle East Rift Zone, the majority of the geochemical effort was restricted to the lower rift and the summit caldera. The sampling network for soil mercury concentrations undertaken by Cox (1981) identified a complicated pattern of mercury concentrations throughout the lower Puna area (Fig. 60). The highest soil mercury concentrations found were generally located within the rift zone, but an analysis of the data showed that soil type and soil pH also had a marked impact on mercury concentration. Making corrections for these effects improved the correspondence between the surface geological expression of the rift zone and the mercury concentrations observed; interpretation of the "fine structure" of the mercury concentrations in terms of the detailed structure of the rift zone did not, however, appear to be feasible.

Radon emanometry data for the same locality (Fig. 61) (Cox, 1980) similarly presented a

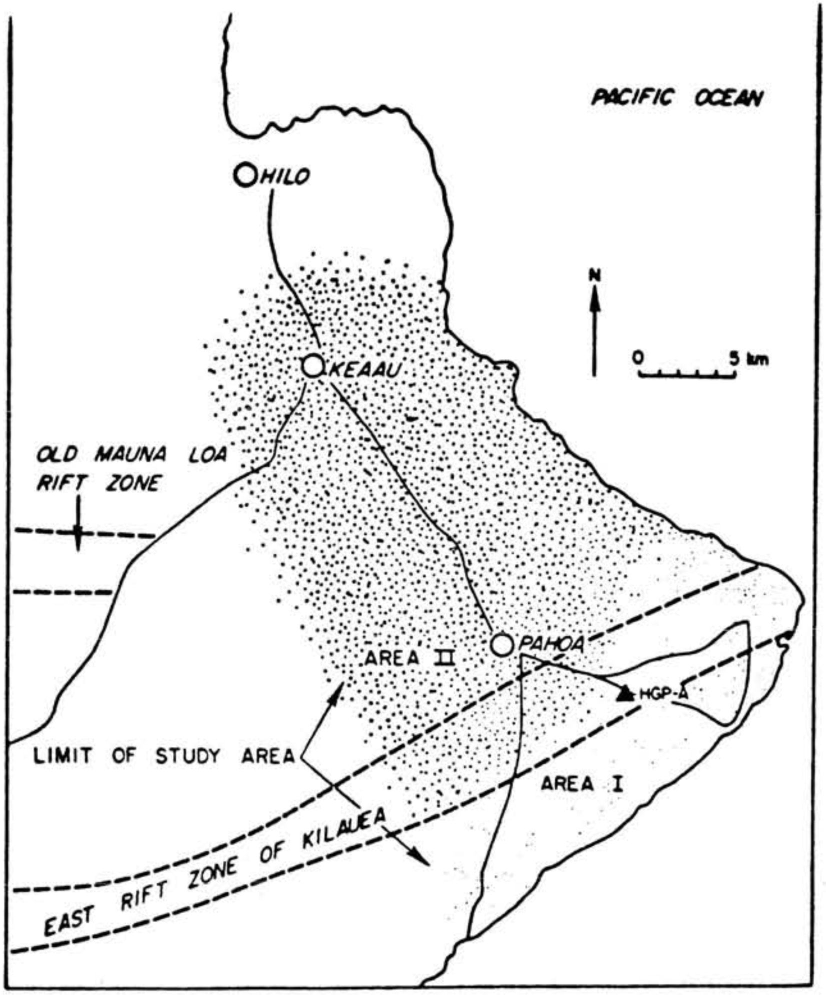


Fig. 57. Map of the Kilauea East Rift Zone (Hawaii is.) showing the inferred locations of high and low subsurface resistivities. Heavy dots correspond to high subsurface resistivity and light dots to low resistivity. Low resistivities are inferred to correspond to areas underlain by thermal fluids or by higher than average salinity fluids. (From Kauahikaua and Mattice, 1981.)

complicated pattern of radon outgassing along the lower rift zone. Even though complexities are present within the rift zone, there appears to be a closer correspondence between known rift zone structures and higher than background radon outgassing rates. This pattern of variable outgassing rates has been interpreted to reflect the presence of a geothermally driven ground gas convection system within the highly fractured and permeable, unsaturated rocks of the lower East Rift Zone (Cox, 1980).

Soil radon and emanometry studies performed around the Kilauea summit (Cox, 1983) also detected very complicated variations in the mercury concentration and outgassing rates. The most notable feature of these surveys was that the levels of mercury and the radon emanation rates were substantially higher in the summit region than those found on the lower rift system; the maximum values found at the summit were factors of 15 and 2 times higher than the maximum values found for mercury and radon, respectively, on the lower rift.

Studies of groundwater and coastal spring sources that have identified thermal fluids on the lower East Rift Zone date back to the early part of this century (Guppy, 1906). More recent investigations of temperature and groundwater chemistry were performed for the HGP geoscience program (Macdonald, 1977; McMurtry *et al.*, 1977; Epp and Halunen, 1979). Epp and Halunen (1979) identified several warm water wells, one having a temperature in excess of 90°C, and coastal springs in lower Puna; temperature profiles obtained by this study indicated

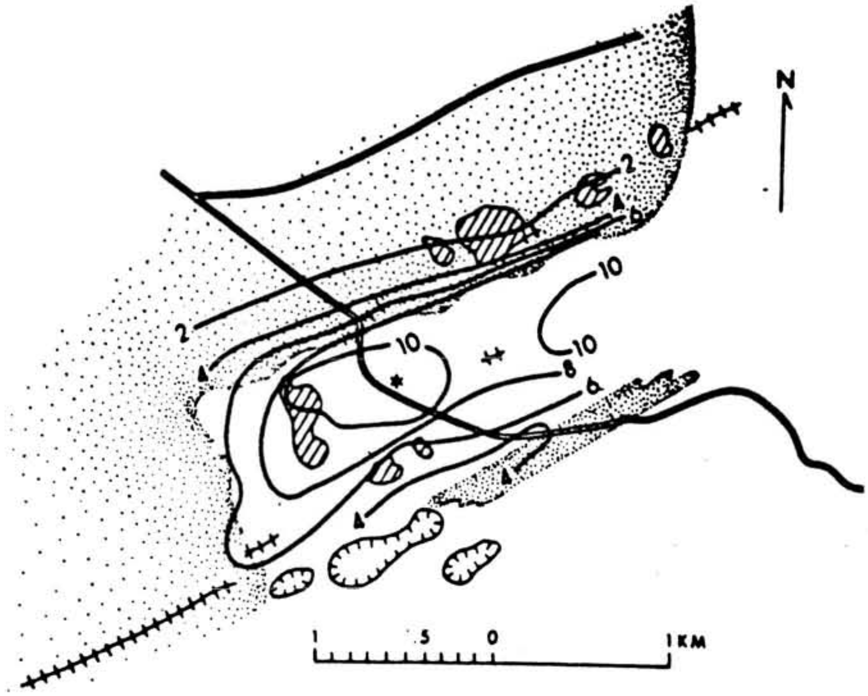


Fig. 58. Interpreted subsurface resistivity contours inferred from *mise-a-la-masse* surveys conducted at the HGP-A well. The star in the center of the drawing is the location of the HGP-A well and the hatched lines are surface cracks. (From Kauahikaua *et al.*, 1980.)

that in some locations a lens of thermal fluid was present, floating on top of a cooler groundwater layer below. These observations suggest that significant quantities of thermal fluids are being discharged from natural vents along the rift zone and that these fluids are being carried along the surface of the basal lens to be discharged to the ocean at coastal thermal springs.

Analyses of the groundwater chemistry in lower Puna performed under the HGP effort (Druecker and Fan, 1976; McMurtry *et al.*, 1977; Kroopnick *et al.*, 1978) identified a positive correlation between silica concentration and groundwater temperatures. These studies also pointed out that significant quantities of seawater were being mixed with shallow basal waters in the area south of the rift zone; this mixing could suggest that the normal Ghyben-Herzberg lens is not present due to convective circulation of heated seawater into overlying freshwater aquifers. Kroopnick *et al.* (1978) and Cox and Thomas (1979) also noted alteration in the chloride/magnesium ion concentration ratios in the thermal groundwaters of lower Puna (Table 10). The latter study proposed this ratio as a qualitative indicator of thermal alteration of saline or brackish water; a quantitative relationship between silica and chloride/magnesium ion ratios was not, however, found.

Exploratory drilling. Two separate phases of geothermal exploratory drilling have occurred on the lower East Rift. The first was essentially a wildcat venture with relatively little surface exploratory data having been gathered, whereas the second was initiated after somewhat more geoscience information had been acquired under the Hawaii Geothermal Project.

The first exploratory wells were drilled on the East Rift in 1961 and 1962. Four wells (2686-01, 2686-02, 2982-01 and 3081-02) were completed to depths ranging from approximately 54 m to 210 m; none was drilled to more than a few meters below sea level. The temperatures encountered in these wells ranged from approximately 40°C to 100°C; hence none was considered to be commercially viable for electricity production. All four of the wells were subsequently abandoned.

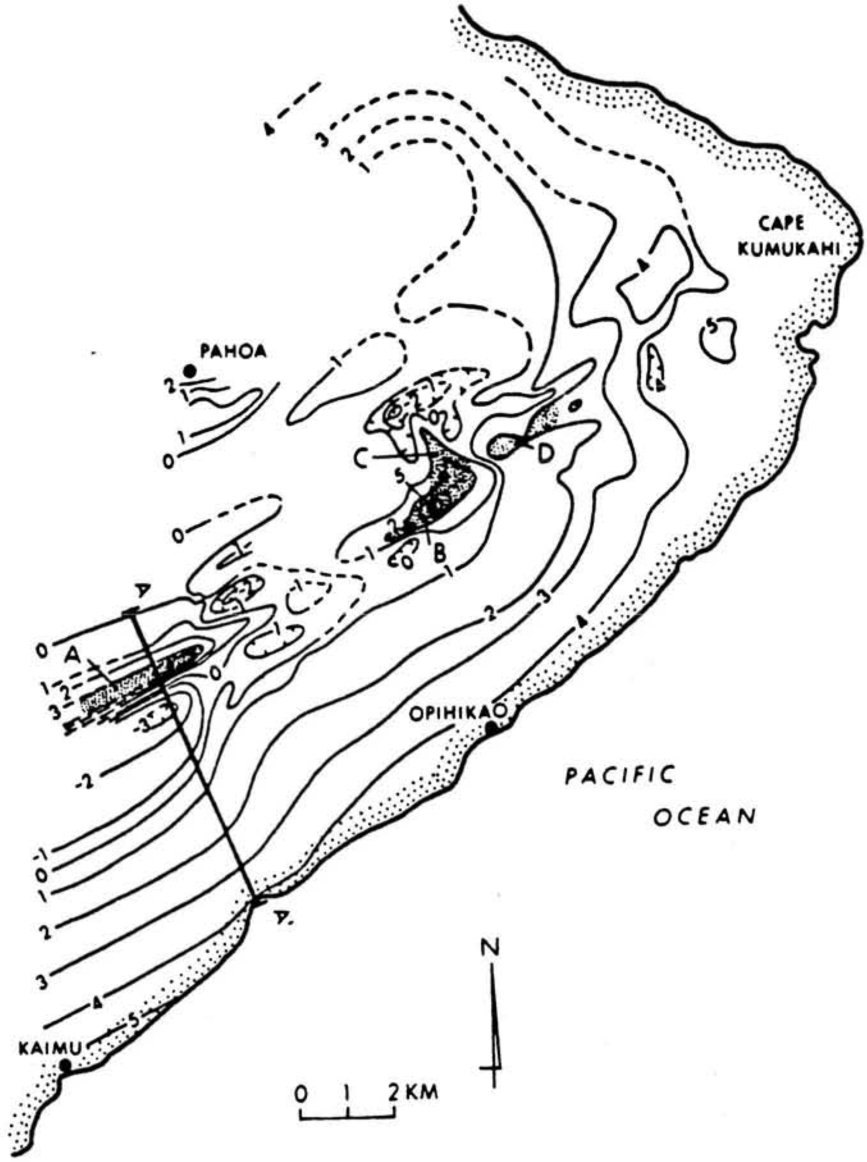


Fig. 59. Shaded areas outline self-potential anomalies identified on the lower East Rift Zone (Hawaii is.). These anomalies formed the primary basis for the location of drilling targets for a deep geothermal research well under the Hawaii Geothermal Project. (From Zablocki, 1977.)

In 1975, a second phase of exploratory drilling was initiated by the drilling of the HGP-A well. This well was drilled upon the completion of a set of geophysical and geochemical surveys which had yielded results suggesting that subsurface thermal anomalies were present in the rift zone. Although the precise target chosen for the HGP-A well was a matter of some controversy at the time, subsequent events have shown that the success of the HGP-A drilling site (2883-01, Fig. 62) was more the result of luck than of detailed geophysical analysis. Initially, the target chosen was in the center of a self-potential anomaly, referred to as "Anomaly A" by Furumoto (1977) (Fig. 63), near the lower edge of the rift zone. Due to the unavailability of land at this location, the proposed drilling site was moved northeast, to the closest available property, on the shoulder of the identified anomaly. The well was drilled to a depth of approximately 1960 m below ground surface and encountered a maximum bottom hole temperature of 358°C. The production capacity, although initially low, has proven to be approximately 50,000 kg/h. The well produces a mixed-phase fluid comprised of 43% steam and 57% liquid at a wellhead pressure of 1200 kPa abs. The reservoir fluid encountered had a moderate salinity and a

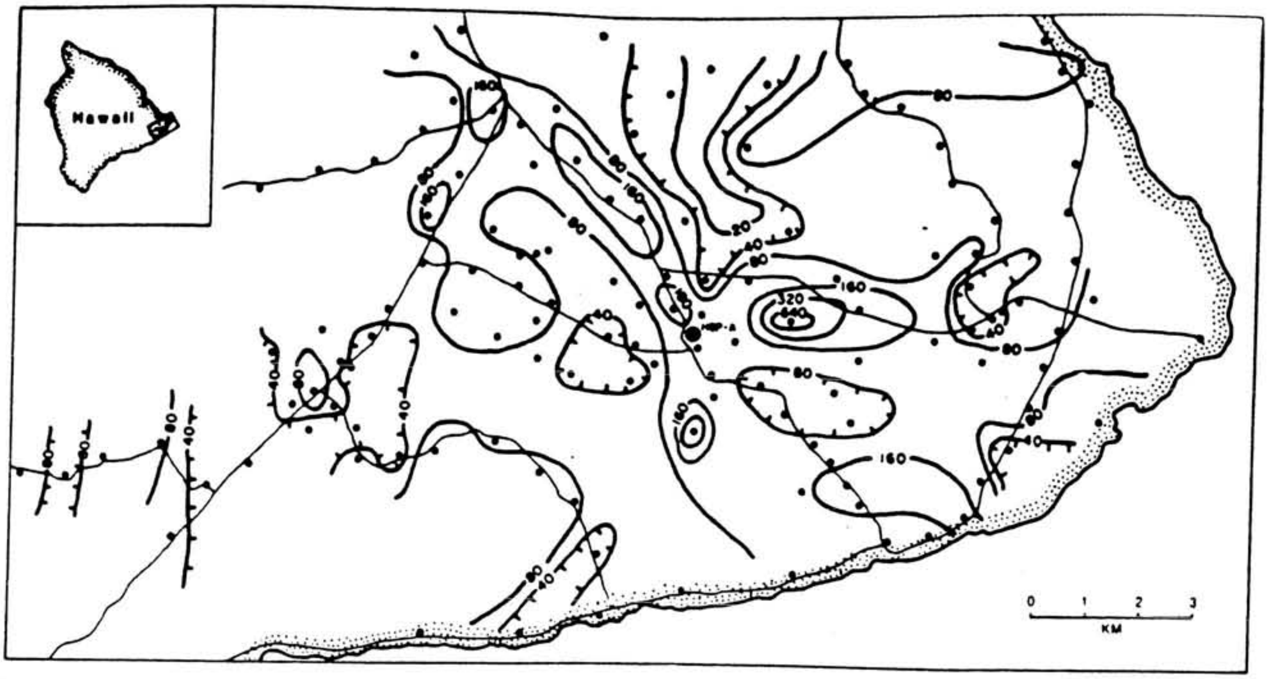


Fig. 60. Soil mercury concentrations found on the lower East Rift Zone of Kilauea (Hawaii is.). Concentrations are presented in parts per billion (ppb) and are contoured geometrically. Dots represent sampling sites. (Redrawn from Cox, 1981.)

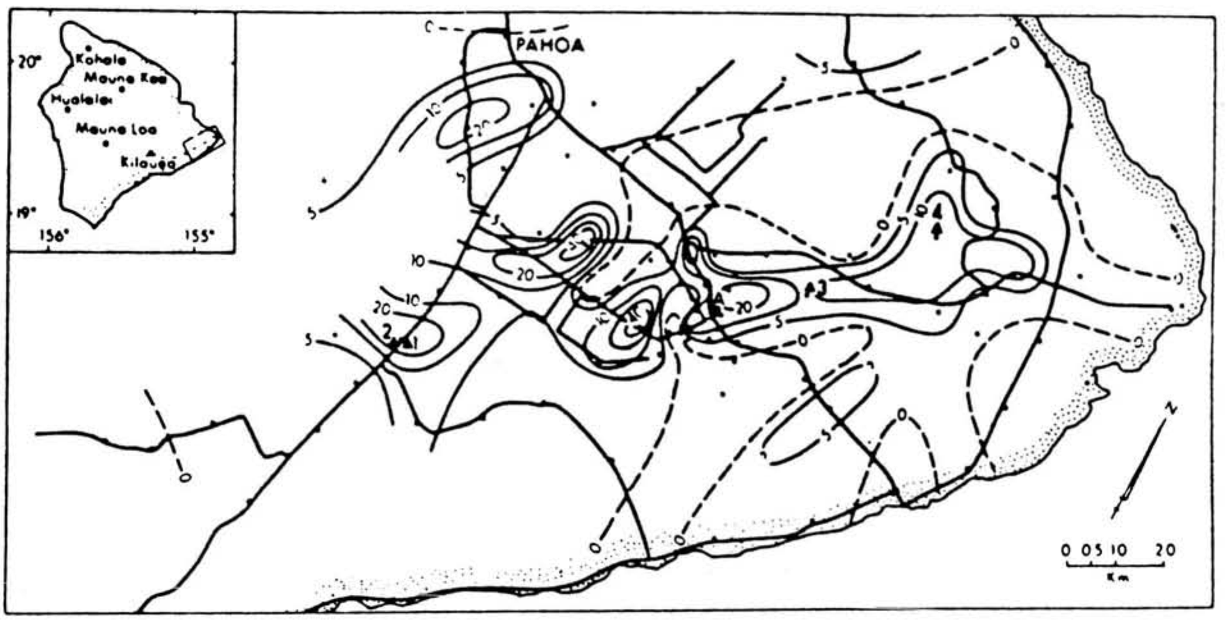


Fig. 61. Map of radon emanometry results for the lower East Rift Zone of Kilauea (Hawaii is.). Results are given as tracks per square centimeter per hour of exposure (× 100), corrected for soil background and contoured geometrically. Dots represent monitoring stations. (From Cox, 1980.)

noncondensible gas concentration indicating that the primary source of recharge to the reservoir is from a meteoric source.

Since production testing at HGP-A has proved that a hot water geothermal resource is indeed associated with the Kilauea East Rift Zone, geothermal exploration companies have completed four additional deep wells within the rift area (2685-01, 2883-02, 2883-03 and 2883-04, Fig. 62). The majority of the data generated by these wells is proprietary; however, it has been reported that all of the wells have encountered high (greater than 200°C) subsurface temperatures. Production rates from these wells have not been uniform, however; two apparently achieved

Table 10. Water chemistry data for thermal wells located in Puna Area, Hawaii island

Sample location	pH	Temp. (°C)	Na	K	Ca	Mg	Cl	SO_4	HCO_3	SiO_2	Cl/Mg	Depth	Elev.	Date
2487-01	7.3	24	64	5.0	12.4	3.8	105.6	22	42	41	27.6	244.5	229.3	11/82
2685-01		>200			Proprietary							>1500	274	
2686-01		54										54	290	
2686-02		102										169.5	295	
2783-01	6.9	55	3333	218	293	295	5380	681	262	59	18.2	97.3	83.5	7/83
2881-01	7.3	38	1188	68	84	102	2042	69	132	24	20	42.7	40.2	7/82
2883-01		358	5058	654	250	0.153	7473	23	60	850	49,100	1966.5	195	2/83
2883-02		>200			Proprietary							>1500	205	
2883-03		>200			Proprietary							>1500	245	
2883-04		>200			Proprietary							>1500	160	
2982-01	6.8	93	2757	300	283	137	5257	335	30	970	38	210.4	171.6	11/82
2986-01	7.4	21	16.7	9.3	4.5	31	4.9	13	51	39	1.6	230.2	216.8	11/82
3081-01	7.2	35	269	20.1	38.5	22.4	390	65	—	70	17.4	102.7	87.5	11/82

Concentrations are in mg/kg.
Well depths and elevations are given in meters.
See Fig. 62 for well locations.

Table 11. Estimated probabilities for geothermal resources

Location	Probability for low to moderate temp. resource	Probability for moderate to high temp. resource
Kauai		
Post-erosional volcanic series vents	N	N
Oahu		
Lualualei Valley	10 – 20%	<5%
Kaneohe-Waimanalo	⩽10%	<5%
(Mokapu Peninsula)	(<5%)	(<5%)
Haleiwa	N	N
Laie	N	N
Pearl Harbor	N	N
Molokai		
West Molokai	I	I
Maui		
Olowalu-Ukumehame	50 – 60%	⩽10%
Lahaina-Kaanapali	<5%	<5%
Honokowai	<5%	<5%
Haleakala Northwest Rift (Pauwela)	10 – 20%	<5%
Haleakala Southwest Rift	30 – 40%	15 – 25%
Haleakala East Rift	I	I
Hawaii		
Kohala	N	N
Kawaihae	35 – 45%	⩽15%
Hualalai		
Summit	35 – 45%	20 – 30%
Lower Northwest Rift	⩽15%	<5%
Mauna Loa		
Lower Southwest Rift (South Point)	I	I
Lower Northeast Rift (Keaau)	<5%	<5%
Kilauea		
Upper Southwest Rift	100%	70 – 80%
Lower Southwest Rift	100%	50 – 60%
East Rift Zone	100%	100%

I = insufficient data available to determine resource probability.
N = not studied during current field survey program.
Note that some of the survey areas has been subdivided (e.g. Hualalai) when the resource probabilities have been found to vary markedly within a given prospect.

economically viable production rates whereas two others have not. It is noteworthy that of the latter two wells, one is located very nearly on the center of the self-potential anomaly ("Anomaly A", Fig. 63) initially chosen as the site for HGP-A; the other is located in close proximity to a second favored site, "Anomaly B" (Fig. 63), identified by Furumoto (1977).

The results of the successful exploratory drilling program on the Kilauea East Rift Zone have proven that a commercially viable geothermal resource is associated with the rift system. The unsuccessful wells that have been drilled have also shown that the confirmation of a resource capable of producing significant volumes of steam cannot be accomplished using currently available surface geophysical or geochemical techniques; subsurface permeability in a given location can apparently only be determined by drilling and testing a deep exploratory well.

Geothermal assessment. The geological, geophysical and geochemical data currently available for the Kilauea East Rift Zone indicate that a geothermal resource is present along the

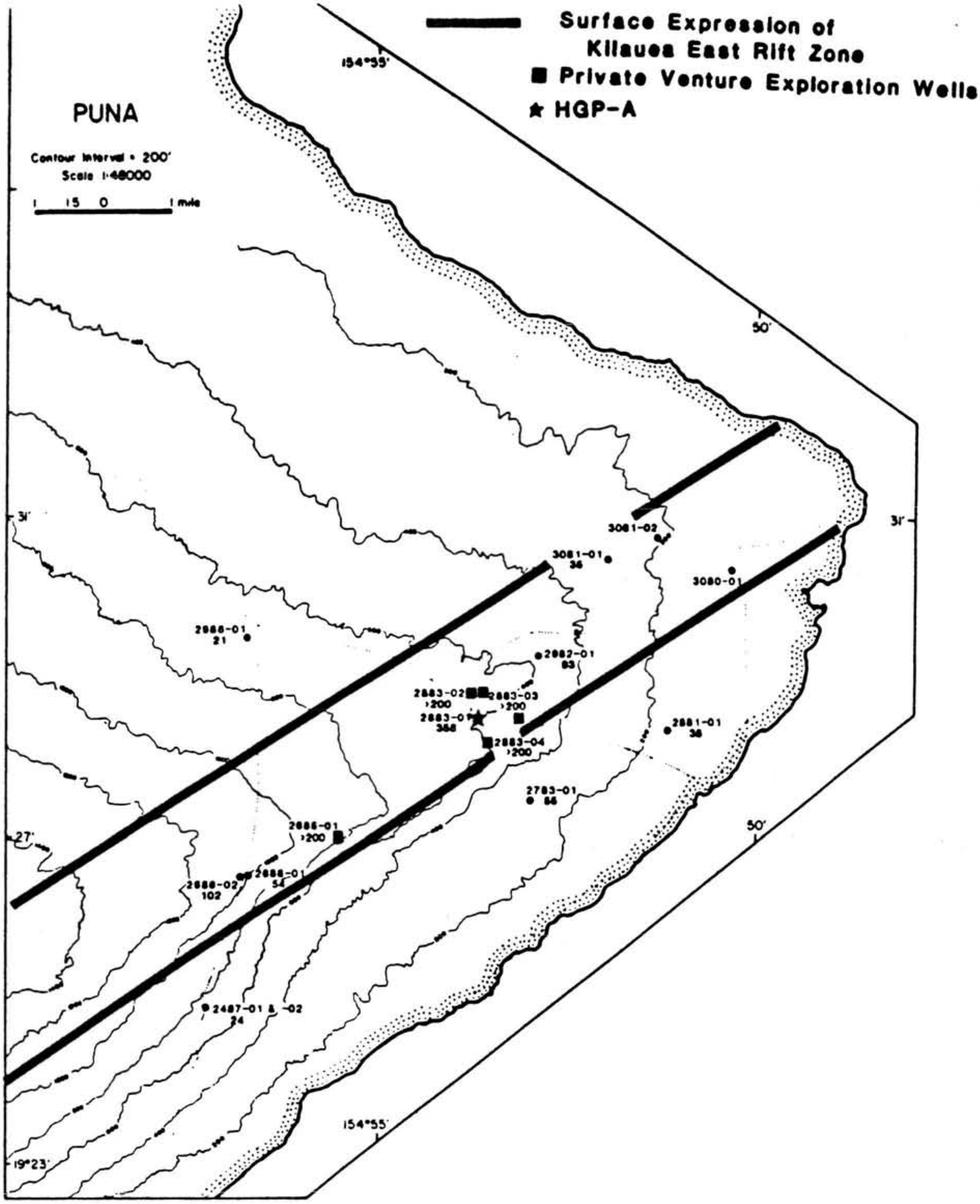


Fig. 62. Map of the Kilauea lower East Rift Zone (Hawaii is.) showing the location of shallow groundwater wells and deep geothermal exploration wells. The upper number corresponds to the USGS well identification number and the lower number to the temperature in degrees Celsius measured at each well. Heavy black lines indicate the extent of the surface expression of the rift zone.

entire subaerial length of the rift area. Deep exploratory drilling on the lower rift has also proven that commercially valuable quantities of steam can be produced from the geothermal system associated with the rift zone.

The probability of a high-temperature geothermal resource being associated with the Kilauea East Rift Zone is, therefore, 100%.

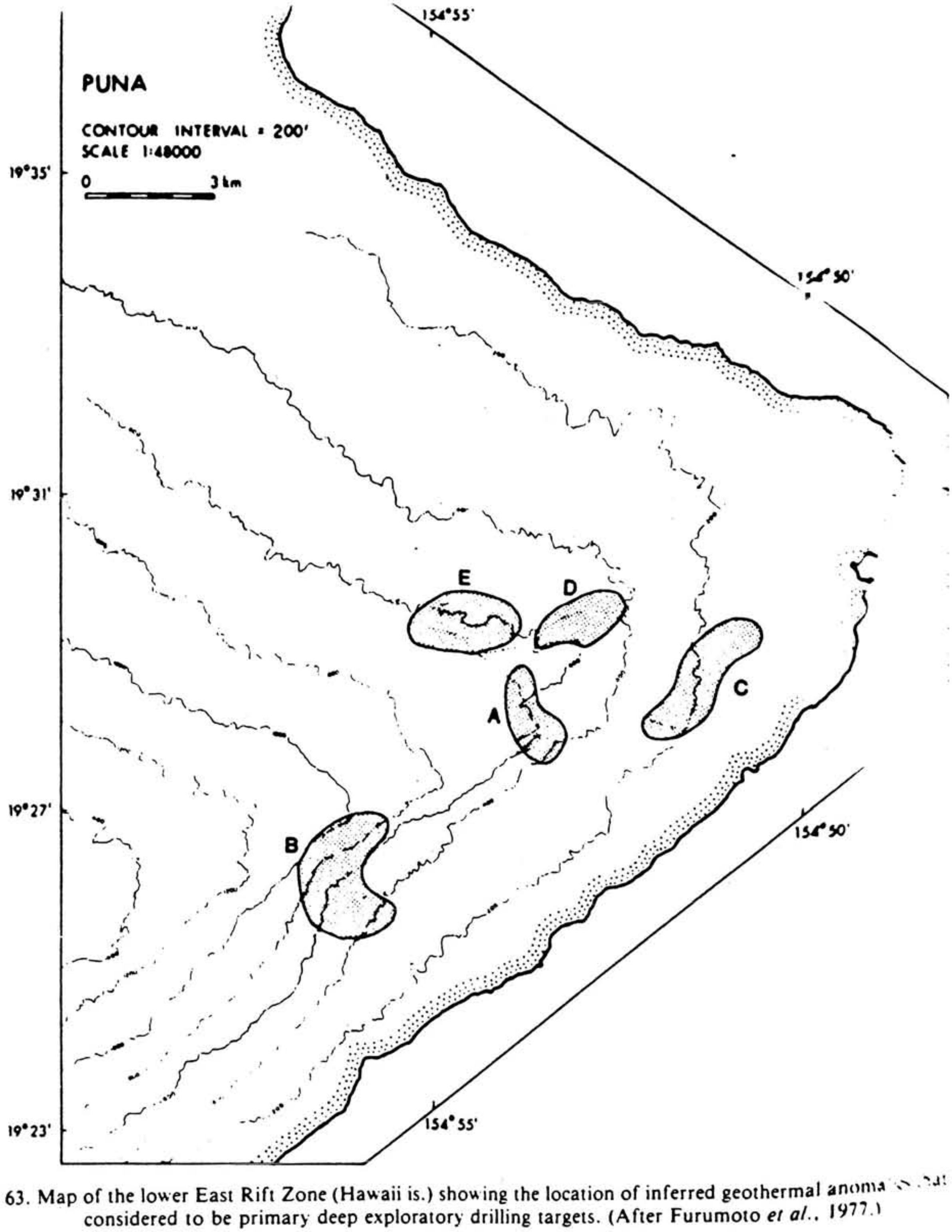


Fig. 63. Map of the lower East Rift Zone (Hawaii is.) showing the location of inferred geothermal anomalies that were considered to be primary deep exploratory drilling targets. (After Furumoto *et al.*, 1977.)

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Figure I-5
CONCEPTUAL GEOTHERMAL SYSTEM

WELLS DRILLED KILAUEA EAST RIFT ZONE

Map #	Name	Location (N/W)	Mo/Yr.	Max Temp. C	Max Depth (M)	Fluids	Operator	1989 Status	Quality of Avail. Data
HA-5	Geothermal 1	19-26-34/154-56-46	'61	54 @ 54m	54	No	Hawaii Thermal Power Co.	Aband.	Poor
HA-6	Geothermal 2	19-26-33/154-56-48	'61	102 @ 167m	170	No	Hawaii Thermal Power Co.	Aband.	Poor
HA-13	Geothermal 3	19-29-13/154-54-55	'61?	93	210	No	Hawaii Thermal Power Co.	Aband.	Poor
HA-15	Geothermal 4	19-30-39/154-51-19	'61	43	88	No	Hawaii Thermal Power Co.	Aband.	Poor
HA-1	NSF Kilauea	19-23-44/155-17-21	'73	139	1262	No	NSF	Aband.	Poor
HA-9	HGP-A	19-28-31/154-53-44	7/76	358	1968	100,000#/hr.	University of Hawaii	Operating	Excellent
HA-4	Ashida 1	19-26-59/154-55-32	10/80	288	2530	?	GEDCO	Aband.	Fair
HA-10	Lanipuna 1	19-28-16/154-53-33	5/81	360	1557	Yes	GEDCO	Aband.	Fair
HA-11	Kapoho State 1	19-28-47/154-53-39	11/81	343 @ 1950	2222	73,000#/hr.	Puna Geothermal Venture (Thermal Power Company)	Plugged	Good
HA-12	Kapoho State 2	19-28-47/154-53-49	4/82	355 @ 2103	2440	41,000#/hr.	Puna Geothermal Venture (Thermal Power Company)	Plugged	Good
-----	Lanipuna 1 ST	19-28-16/154-53-33	6/83	211 @ 1646	1911	Yes	GEDCO	Aband.	Good
-----	Lanipuna 6	19-28-40/154-53-22	6/84	168 @ 1290	1510	No	GEDCO	Aband.	Good
-----	Kapoho State 1A	19-28-47/154-53-39	9/85	369	1983	78,000#/hr.	Puna Geothermal Venture (Thermal Power Company)	Plugged	Good

9/22/89 - 1106B (revised)